CBRS Infrastructure and Devices 2017

Abstract: This document is an end-to-end review of the CBRS ecosystem to assess its potential growth, market size, and timing. Infrastructure, SAS connectivity, and core network issues are balanced with handset, CPE, and IoT device availability.

Four different business model scenarios are investigated to fully assess the potential of the CBRS market for mobile operators, cable operators, neutral hosts, and enterprises.

Joe Madden

Kyung Mun

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MOBILE EXPERTS

TABLE OF CONTENTS

CHARTS

FIGURES

CBRS Infrastructure and Devices 2017

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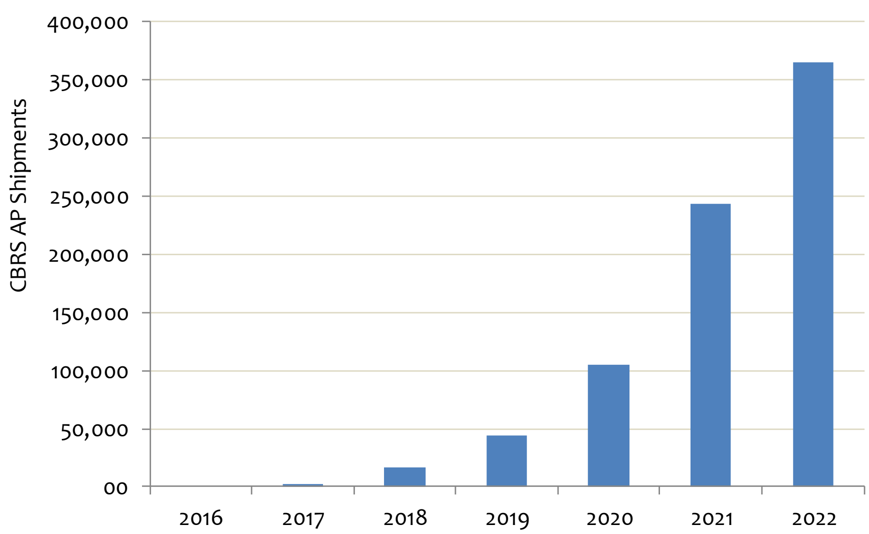
1 EXECUTIVE SUMMARY

Most new initiatives in mobile telecom don't move quickly, because the mobile operators are the principal drivers behind the market and they don't do anything quickly. But the LTE market is starting to transition from a mobile operator-led market to a more open environment where enterprises, cable operators, and mobile players all have a role.

CBRS is coming together quickly, because the shared CBRS spectrum can be effectively used for many different purposes. This report investigates five primary business models:

- Fixed Wireless Access
- Outdoor deployment by mobile operators for capacity augmentation;
- Outdoor deployment by cable operators to reduce MVNO costs;
- Indoor deployment by enterprises and/or neutral hosts for general smartphone access;
- Private LTE for either access or IoT applications.

Because CBRS market growth will be driven by many different business models, we have high confidence that the market will grow quickly. Some fixed-wireless deployments are already underway. Verizon and T-Mobile are moving aggressively, each for slightly different use cases. Cable operators are moving aggressively to upgrade their networks. And the huge industrial/enterprise market is waking up, with large VARs and system integrators putting together CBRS product plans for very wide applicability.



Source: Mobile Experts

Chart 1: CBRS Small Cell Shipments, 2016-2022

The forces that normally hold the LTE market back will be restrained in this case. Mobile operators are normally very cautious about the use of their licensed spectrum, so they delay and test every idea for years before wide implementation. CBRS underlay infrastructure won't interfere with other LTE networks so that concern is greatly reduced.

In addition, the cost of CBRS networks will likely be lower than the cost of licensed LTE or DAS alternatives for both operators and enterprises due to the nature of shared spectrum sharing. The favorable economics of CBRS access will drive the decision making at cable and mobile operators to use CBRS in many locations currently served by small cells or Wi-Fi access points.

Finally, the wider CBRS ecosystem is lining up to take remaining friction out of the system. SAS vendors will be offering services to coordinate with core networks, making authentication easy for neutral hosts and enterprises. System integrators such as Accenture, IBM, and others are looking seriously at how to package CBRS communications solutions for their major enterprise customers, related to both access and IoT.

Handsets will be a bit slow to build critical mass, with the first handsets in 2018 and major flagship-level smartphones coming in late 2019 to 2020. Early IoT modules, access points, and fixed-wireless nodes are already available, so the FWA and Private LTE markets do not need to wait for smartphone "critical mass" to build.

A few regulatory changes are likely to happen, with longer terms for CBRS Priority Access Licenses (PAL) and renewability for licenses so that users can make long term plans. Other changes related to the regional size of PAL license areas may change, but we expect that some local licenses will be possible to allow for growth in the rural fixed wireless and enterprise areas.

Overall, we anticipate rapid growth, with shipment of 300,000 access points for about $0.5 billion in 2022, and more than 1 billion handsets, CPEs, and IoT devices shipping over the next five years.

2 MARKET DRIVERS

Almost everyone has noticed that competition is heating up in broadband service to American customers. The comfortable and profitable mobile telecom market is quickly becoming uncomfortable, as cable operators and alternative ISPs begin to offer wireless services with many of the benefits of mobile standards.

We won't waste time here in showing the usual charts of data growth toward Exabytes. The more relevant trends are below the surface: ARPU has peaked and revenue is declining for the big mobile players. Verizon and AT&T won't be able to control the market any longer, as T-Mobile grows in stature and other options are rising. Cable operators have launched effective MVNO and Wi-Fi networks which provide a mobile-like experience at lower cost. (See Section 3 on Cost Analysis).

The CBRS band and shared licensing rules that have been implemented by the FCC represent a new battlefield in this competition between Mobile and Cable. So far, the business models are unproven and the technology is still in a trial phase. But clearly the CBRS arena will be critical for various new business models to sprout in the fiercely competitive wireless market.

Several new business models can take advantage of the light licensing of CBRS:

1. Fixed Wireless Access: One of the simpler use cases for CBRS involves outdoor infrastructure and fixed broadband service for residential or enterprise customers. For simplicity, we focus on the residential case.
2. Private LTE Networks: Private enterprises can implement their own networks as a way to enhance security, to create IoT connectivity for operations, or to simply save money compared with telecom services.
3. Neutral Host Access: A neutral host can implement a CBRS network instead of a more costly DAS system, to provide coverage in a venue.
4. MNO Capacity Augmentation: Mobile operators can add capacity by adding the CBRS band on top of their existing LTE spectrum.
5. MVNO Mobile Offload: MVNOs such as cable operators can pay exorbitant fees to use a mobile network, so they're highly incentivized to offload traffic to another medium.

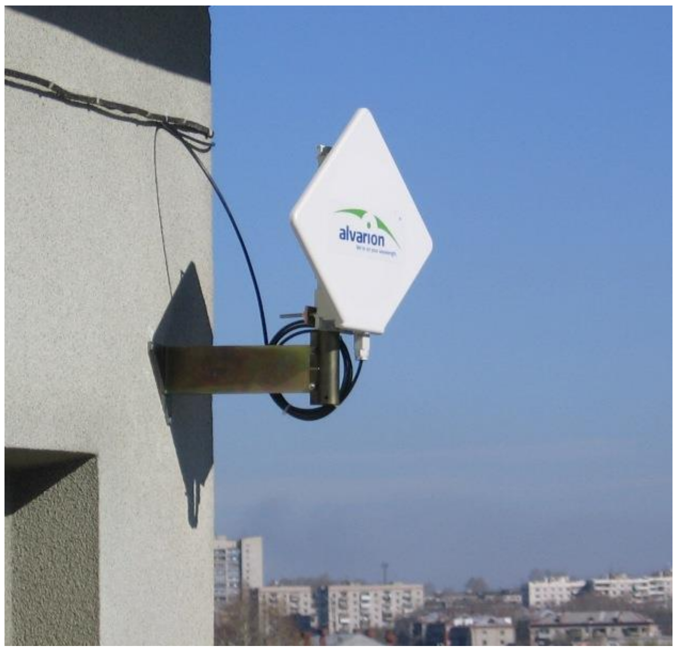
Fixed Wireless Access

More than 28 million Americans still use DSL, power line, or satellite Internet service providers because they can't get decent broadband services to their homes.[1] Assuming an average revenue opportunity of $50/month, this segment represents almost $17B per year in

[1] FCC Internet Access Service report, June 30, 2016

broadband service revenue that is generally unmet due to the high cost of passing rural and suburban homes with copper, coax, or fiber.

Fixed wireless access (FWA) presents an opportunity to change the "underserved" rural and suburban markets, improving data speed for these 28 million homes. Broad licensed spectrum below 4 GHz is difficult to find, and all available scraps have already been auctioned to the major telecom carriers for LTE operations. But while Verizon and AT&T are chasing big ROI targets in the urban and business markets, the LTE spectrum is essentially idle in rural areas.



Source: Alvarion

Figure 1. A typical Wi-Fi based FWA CPE

The concept of spectrum sharing works much better than exclusive licenses for rural FWA. In a rural area, a local entrepreneur can set up a CBRS network based on fiber and wireless backhaul to a central location, with several subscribers sharing each CBRS access point.

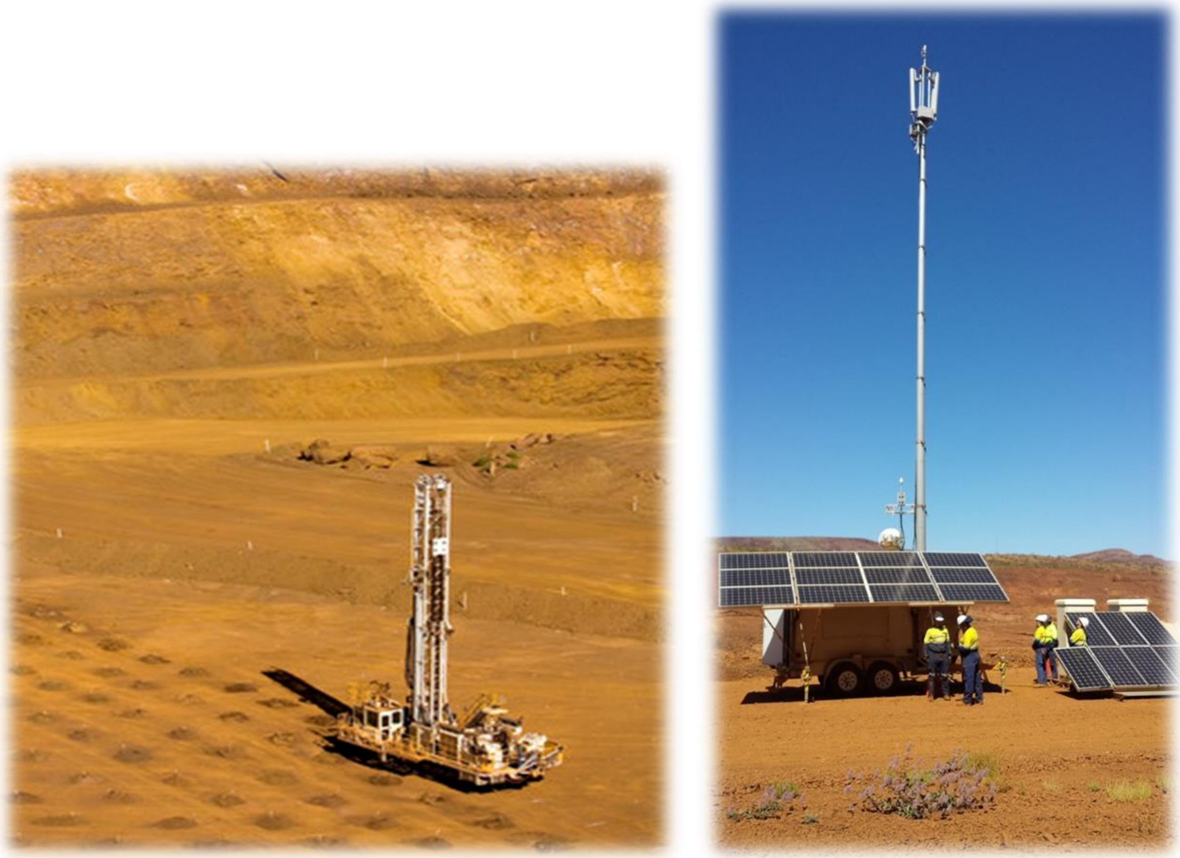
Rural customers are not the only opportunity here. Many urban customers in the United States are stuck with only a single choice for broadband access, and the monopoly status of these providers results in predictably horrible service. Consistently, surveys conducted by Consumer Reports have rated Comcast, Time Warner Cable (now Charter), and Charter among the "bottom dwellers in overall customer satisfaction". At the same time, the price charged by these monopolies has increased. In San Jose, California, the monthly fees on Comcast for basic residential broadband service have increased from $72 to $139 over the past five years, with a lot of confusing changes to plans, fees, and service charges along the way. The average cable bill is much lower at about $65, but pockets like San Jose are full of desperate customers looking for an alternative.

In short, the pent-up demand for alternative broadband services is strong but fragmented, based on various levels of service and regional market competition. The FWA opportunity is not well suited to a one-size-fits-all solution, but can be addressed by hundreds of small entrepreneurs, or by a nationwide company that has many tools in their box.

Private LTE Networks

As industrial enterprises rely on broadband connectivity more, the opportunity for private LTE-based communications networks is starting to diversify and grow. Many interesting use cases have arisen during the past three years:

- Rio Tinto has 15 mines, four shipping terminals, and its own railway in Western Australia. The company uses autonomous mining and transport in a great deal of their network based on a highly developed private LTE network. The Rio Tinto network was launched in August 2013 with four solar-powered trailers that are constantly moved around as mining operations literally change the landscape and terrain around them. Other mining companies such as BHP, Glencore Xtrata, Vale, Freeport McMoRan, and Fortescue are following the lead of Rio Tinto with their own networks and automation. Rio Tinto uses licensed LTE spectrum, and some of the others plan to use 5 GHz LTE-Unlicensed (LTE-U). American mining companies can be expected to use CBRS-based LTE because of high RF power limits and cheap availability of products in the 2019 timeframe.



Source: Rio Tinto

Figure 2. Rio Tinto's Automated Drill and LTE Infrastructure

- Industrial operations are a large potential market. As one example, DSME (Daewoo) and SHI (Samsung) operate automated shipbuilding operations in Korea where LTE networks control thousands of welding machines for higher quality welding joints. Where unlicensed wireless technologies are replacing Fieldbus or Ethernet wires in some factory settings, larger industrial operations will need LTE for longer range connectivity with low latency and high reliability. GE Digital is investing in a trial network with Nokia and Qualcomm in the CBRS band, in its Predix lab in California. This type of American investment in manufacturing and industrial operations will translate into growth momentum in CBRS-based private LTE.

Source: SHI

Figure 3. Controlling Automated Welding in a Shipyard

- Transportation operations are often discussed for Private LTE networks. Many automated cranes and ground vehicles use RFID technology today, but LTE could give them a boost in range, speed, and flexibility. In addition, LTE could support video operations which would improve safety and oversight of these massive moving structures. CBRS systems can be installed for a locally secured network, without any fees to mobile operators for large data streams such as video.

Source: Qualcomm

Figure 4. Use of Private LTE in Port Operations

- Remote operations need automation as well. Shell has introduced a "Sensabot" to conduct routine checks on remote equipment in remote or dangerous locations, dramatically lowering the cost of monitoring oil & gas exploration and drilling sites. One additional aspect of this kind of automation is that often the Oil & Gas industry has locations with potentially explosive gases and other safety hazards for human technicians.

Source: Royal Dutch Shell

Figure 5. A robot used to monitor remote oil & gas production

- Point-of-Sale terminals present challenges in security, portable operation, data speed, and reliability. In large venues, portable POS terminals are best implemented on a private network for a secure and predictable connection, every time.
- In addition to all of the above, Public Safety is another key business area for Private LTE infrastructure suppliers. In some cases (such as FirstNet), the network is arguably not a "Private LTE" network since the infrastructure can be made available for the general public's broadband use. However, to the extent that these networks are funded by public safety agencies we count them as a Private LTE network. The growing need for video data in firefighting and law enforcement is now driving much stronger growth in public safety investment for wireless infrastructure, and LTE is quickly moving to the top of the list of "known technologies" that are trusted by key agencies.

Today, the Private LTE market is not as big as other analysts claim. After asking several vendors for specifics, we can only identify a few real installations of Private LTE networks worldwide. One challenge for Private LTE is the need to coordinate on spectrum with the mobile operators that own exclusive spectrum rights. Rio Tinto has the wherewithal to negotiate a deal with Telstra….but most manufacturing plants, retail malls, and public safety agencies would not think of trying to sublease licensed spectrum.

CBRS can change the dynamics, to open up an easy-to-use product line in which a vendor can simply sell a solution to the enterprise. While this model only works in the USA, the MulteFire equivalent could work on a global scale in the same way.

Neutral Host Networks

Stadiums, large hotels, and airports in the USA are already generally outfitted with DAS systems because the DAS can provide a "neutral" communications platform, meaning that any mobile operator can utilize the coverage for its subscribers. However, the existing DAS infrastructure is limited to 3G in some cases. Continuous upgrades with LTE and higher order MIMO will drive many DAS venues toward very expensive upgrades, as new cabling, amplifiers, and antennas will be needed.

At the same time, many smaller buildings in the US market have not been equipped with DAS infrastructure because the high cost of DAS makes an ROI problematic for the operators. Verizon and AT&T feel that small buildings are not worth the effort to coordinate and deploy a DAS.

CBRS infrastructure offers a good alternative here. Instead of expensive DAS equipment with high capacity and independent radios for each operator, a CBRS network can function independently of each operator's spectrum, and offer shared access for everyone.

This is not a magic solution…and some operators will not like this approach because of the loss of control over the user experience. In particular, operators that take pride in the quality of their networks do not want to relinquish control to a neutral host company (such as Crown Castle, Extenet, or others). The end user will continue to think that the voice and data services inside the building are offered by the major carrier….so any loss in quality will hurt the carrier's reputation.

So, there are challenges with gaining acceptance and cooperation from the mobile operators, but this solution has the elegance of low cost shared infrastructure and the ability to provide seamless coverage in millions of buildings across the United States.

One additional challenge for the Neutral Host business model is the dependence on smartphone platforms to adopt CBRS. Today, Apple and Samsung are not actively working to insert CBRS into their 2018 handsets. We expect second-tier smartphone vendors to introduce CBRS support in late 2018 to 2019, with Samsung products in 2019 and Apple in late 2019 to 2020. This means that the investment in public indoor infrastructure is at least a few years away.

Enterprise Access Networks

One variation on the "neutral host network" is the possibility of an enterprise offering their own network for indoor access via LTE. A hotel chain, for example, may want to install CBRS access points on every hotel floor, to offer LTE service to guests no matter which operator they use. The enterprise will encounter the same challenges as a neutral host with regard to gaining the cooperation of the operators.

This scenario is somewhat similar to the Hotspot 2.0 initiative, which worked great from a technical point of view but has gained commercial acceptance very slowly due to reluctance by the operators to agree to roaming on third-party Wi-Fi hotspots. In the CBRS case, the SAS vendors and neutral hosts may be able to solve the cooperation problem by facilitating core network authentication, aggregating all of the core connectivity so that the big operators aren't required to deal with every individual building project.

In the Mobile Experts forecast, we count Neutral Host and Enterprise Access networks as a single category, "Enterprise/NH" because it's difficult for us to determine the final business model at this point in time. The system integrators and neutral hosts may take the lead to own the CBRS infrastructure and provide a service, or enterprises may own the infrastructure. Either way, we expect strong involvement from the system integrators to make sure that the operator coordination and SAS coordination are done seamlessly.

Mobile Network Capacity Boost

One strong possibility in the upcoming CBRS market involves direct investment in CBRS networks by the mobile operators themselves. Under the original CBRS rules with 3-year, one-time renewable licenses and small license regions based on census tracts, the mobile operators were not very interested in pursuing Priority Access Licenses in the CBRS bands. They may have considered operating radios in the 3.5 GHz band under GAA licenses, but in general the rules made major operators lukewarm about CBRS investment.

Recently, however, the FCC has started to seriously consider changes to the rules which would extend the license term possibly to 10 years, with renewability, and for larger license regions. These modifications would drive the mobile operators to bid for PAL licenses, raising substantially more revenue for the FCC's auction process. Incumbent users and small wireless ISPs have quickly moved to oppose the changes, so we can expect some political arm-wrestling for the next year or more regarding the terms of PAL licenses.

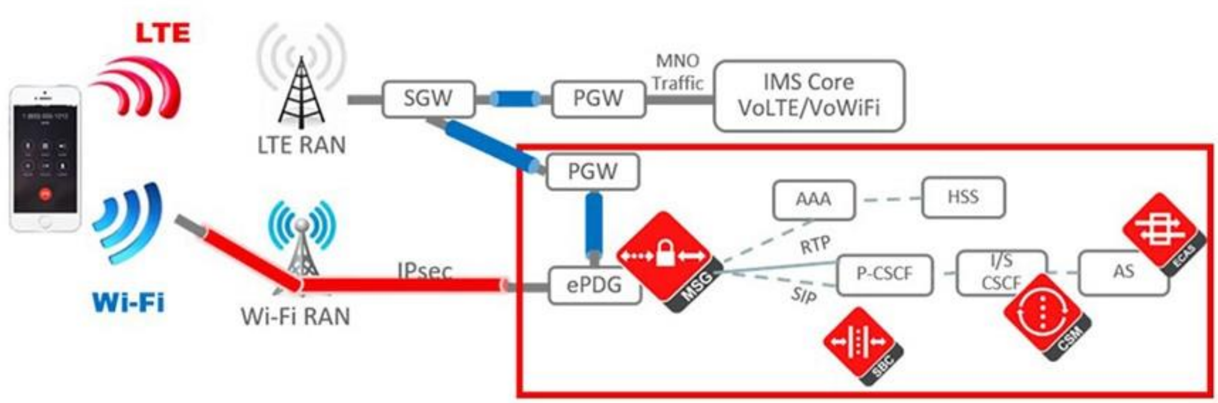
We cannot be certain, but we believe that the FCC will change at least some of the PAL licensing rules to drive a more active and lucrative auction. Assuming that this happens in the 2018-2019 timeframe, we believe that Verizon and others will support deployment of small cells with CBRS radios built in.

In the case of mobile operator deployment, a key catalyst will be the availability of CBRS functionality in major smartphone platforms. Currently we anticipate second-tier handsets to support CBRS in the 2018 timeframe, and major platforms will be launched in 2019 to 2020. The major carriers will not be in a rush to deploy CBRS hardware during 2018, but during 2019 we expect them to begin adoption of CBRS in their outdoor small cell platforms, to be a step ahead of the smartphone products.

MVNO Offload for Cost Reduction

A few cable operators in the US have negotiated MVNO arrangements with Verizon, and are forcing their way into the mobile market. Verizon has gone along with this plan as a result of AWS spectrum purchase agreement with the cable operators. As an MVNO host and an owner of the mobile network, Verizon has the means to check on the potential threat of cable operators' mobile services.

Because the mobile LTE data is so expensive, the MVNOs are motivated to come up with other ways to offload traffic to minimize the "rental" cost of network service fees paid to host mobile operators. As one example, Comcast has deployed over 18million Wi-Fi hotspots throughout their cable footprint and they can currently provide a spotty but widespread cable Wi-Fi service.[2] The main problem for Comcast is the lack of mobility and continuity in their coverage. Despite the high pricing, Comcast can use the Verizon network cost-effectively if only 10% of their data is actually passing through Verizon, and 90% of the data is covered by Wi-Fi or CBRS.



Source: Oracle

Figure 6. A typical MVNO architecture for cable operators that run a Wi-Fi network

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[2] Comcast xfinity mobile web page: https://www.xfinity.com/mobile/support/article/221762167/

By upgrading their Wi-Fi hotspots to dual-mode CBRS and Wi-Fi hotspots, Comcast can substantially increase their coverage footprint and the reliability of their wireless coverage. For urban users within the Comcast footprint, we estimate that more than 95% of the traffic could be covered by the existing AP locations. For the entire rural and urban Comcast footprint, roughly 80-90% of traffic could be covered. This would reduce Comcast's dependence on Verizon substantially, and possibly could result in a profitable mobile service.

Challenges to CBRS: Business Model Hurdles

There are two clear hurdles to major investment in the CBRS market:

1. Mobile operators might not support authentication on their core networks. This is essentially the issue that has limited deployment of Hotspot 2.0: without enthusiastic support from a lot of global operators, the technology never gains critical mass.

   When a smartphone user enters a building with a CBRS access point, the ideal case is for the phone to automatically recognize the CBRS network, and send a message to authenticate itself through the CBRS network. The neutral host or enterprise that owns the CBRS access point will pass the request on to the core network of the relevant mobile operator, to verify that this is a valid user at a minimum. Other policy, charging, QoS measurement, and similar PCRF functions in the core network would also be desirable.

   The interactions with the core network can be brief, and if the local enterprise is sponsoring "free" wireless coverage in the building, the charging and policy functions can be rendered irrelevant. But in all scenarios, we believe that a basic SIM authentication function and operator voice communication services must happen.

   If the mobile operators choose not to support authentication, then third-party CBRS deployment for public wireless access will grind to a halt. FWA and other private LTE networks can proceed, as companies like Extenet have done with Cal.net and Paladin Wireless using a separate core network. But serving "public" wireless access to all comers will come slowly—like Hotspot 2.0—until the SAS vendors or neutral hosts can aggregate the core connectivity and make it easy to "light up" a building.

2. Smartphone adoption is lagging behind the development of infrastructure. For enterprises and venues to use CBRS for improved access inside the building, then a normal user's phone must have CBRS capability embedded into it. Today, neither Apple nor Samsung are actively designing RF filters or software into 2018 handsets to enable CBRS.

In the smartphone market, there are multiple 3.5 GHz services worldwide that are under consideration, and the CBRS band is one of many possible bands, including new 5G bands in the same C-band spectrum range. The handset community is currently considering alternative approaches to handling multiple 3.5 GHz options (see Section 4 for a more detailed technical review).

In the end, we believe that second-tier handset suppliers including Google/Pixel and a few others will support CBRS with basic capability in 2018. Massive 5G trials in China at 3.5 GHz will drive Huawei, Oppo, Vivo, and Korean handset vendors to support smartphone options. Major flagship phones (Galaxy class and Apple) are not likely to include CBRS capability until the second half of 2019, or possibly 2020.

Based on this timeline, we do not expect to see a large percentage of US subscribers with CBRS capability in their handsets until late 2020 or later. This will set the timeline for many wireless access projects.

Changing Dynamics in Fixed vs Mobile Competition

As mobile operators and cable operators compete more directly over the next 3 years, we expect some of the policies and decisions of the operators to change. The strongest mobile operators (like Verizon) have not used Wi-Fi much, preferring to focus on the highest quality with LTE. On the other side, big cable operators have built out Wi-Fi networks widely… and are finding that continuity of coverage is a problem in growing their wireless business.

Both sides are looking for something in between: A network technology that is cheap, but using LTE technology for high quality and broad coverage. Our cost analysis (Section 3) indicates that both MNOs and MSOs will find CBRS attractive.

Mobile Experts anticipates that the entry of strong cable competitors will open up the market. Hotspot 2.0 did not grow quickly because of lack of support from the mobile giants. However, if Comcast and Charter agree to cooperate with enterprise LTE and neutral-host CBRS systems, then Verizon and AT&T will be forced to participate as well. We believe that, five years from now, operators will generally be more open to private in-building initiatives.

3 COST ANALYSIS

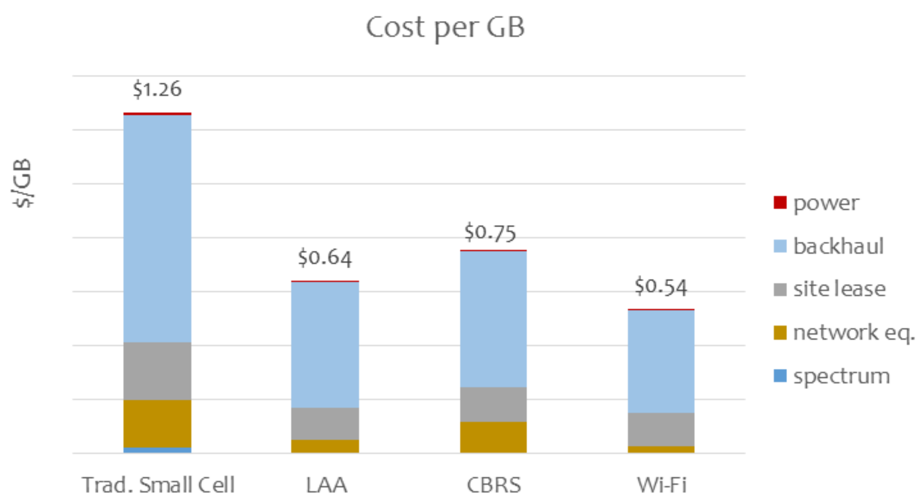
As mobile operators continue to battle data-traffic growth challenges and seek cost-effective solutions to meet ever-increasing demands and expectations of consumers, LTE-U/LAA, CBRS, and MulteFire will provide some relief. Until the millimeter wave band ecosystem matures, the unlicensed 5GHz and shared 3.5 GHz bands represent near-term spectrum opportunities upon which to run LTE services. With the relevant 3GPP standards completed and device and infrastructure ecosystems quickly maturing, operators have many options to consider as they begin to leverage the unlicensed and shared bands with LTE in route to 5G NR transition.

Economics of LTE-U/LAA, CBRS, and Wi-Fi

The economics of leveraging unlicensed spectrum vary by technology, and target use cases. There are many factors that contribute to an operator choosing one technology over others. The decision can vary by specific regions within the operator's footprint as well. For instance, an operator with a limited spectrum holding is more likely to consider LTE-U/LAA small cells to leverage the 5GHz unlicensed or CBRS bands. On the other hand, an operator with extensive and mature Wi-Fi footprint may consider LWA in order to maximize its Wi-Fi investments. For others with a large inventory of licensed spectrum (e.g., Sprint with 2.5 GHz spectrum), LTE-unlicensed technologies like LAA offer little value. Sprint has enough spectrum, just not enough capital to deploy that spectrum.

For operators with impacted spectrum, CBRS is an attractive option from an economic point of view. The high RF power limits of CBRS will translate into longer reach for each small cell, making widespread coverage better for CBRS than for MulteFire at 5 GHz.

There are many factors to consider in network technology choices, including operational complexity, internal process coordination, device ecosystem impact, etc. Understanding basic unit economics is a good place to start. The below figure shows the unit costs of delivering a Gigabyte (GB) of data over a traditional small cell using licensed spectrum vs. a list of unlicensed technologies including LAA vs. CBRS vs. Carrier Wi-Fi. The unit cost advantages of unlicensed technologies (LAA, CBRS and Wi-Fi) over traditional licensed small cell stem from a simple fact that free or cheap unlicensed/shared bands can be used to increase effective cell capacity. The slightly higher unit cost of CBRS vs. LAA and Wi-Fi, is due to higher equipment cost associated with SAS burdened cost. Overall, the unit cost of delivering a GB of mobile data using unlicensed and shared spectrum technologies can be about one-half the cost of using a traditional small cell using licensed spectrum.



Source: Mobile Experts

Figure 7. Comparative Cost per GB of LAA vs. CBRS vs. Wi-Fi

The following assumptions are used to calculate the monthly $/GB unit costs for the different unlicensed technologies. The one-time CAPEX line items such as spectrum and radio equipment costs are converted into monthly costs based on estimated depreciation schedule of the line items.

Traditional Licensed Small Cell		
Element	**Cost estimate**	**Notes**
Spectrum cost	$2,800	$1.75/MHz-pop average cost based on recent AWS spectrum auction; 20-year depreciation
Radio equipment	$5,000 /	LTE BBU/RRH combo; 5-year depreciation
Site lease	$100/month	avg. cost of muni pole attach cost in top US markets
Backhaul	$400/month	2-strand dark fiber cost or high-capacity lit service
Power	$4/month	Based on 20-50W base station power consumption
Effective Cell capacity	475 GB/month	Max. cell capacity with 6% average monthly utilization rate (small cells are more peaky than macro since they have smaller footprints)

Source: Mobile Experts

Figure 8. Cost Assumptions for Traditional Small Cell 'Cost per GB' Calculation

LTE-U/LAA Small Cell		
Element	**Cost estimate**	**Notes**
Spectrum cost	$560	10x10 FDD LTE with 40MHz of unlicensed spectrum; variable spectrum cost is lower than traditional Small Cell case as LAA footprint is smaller, thus less subscribers; 20-year depreciation schedule
Radio equipment	$2,500	LAA multiband radio; 5-year depreciation
Site lease	$100/month	avg. cost of muni pole attach cost in top US markets
Backhaul	$400/month	2-strand dark fiber cost or high-capacity lit service
Power	$4/month	Based on 20-50W base station power consumption
Effective Cell capacity	854 GB/month	Max. cell capacity based on 54Mbps of LAA coexistence throughput (from NI testing) with 5% average monthly utilization rate

Source: Mobile Experts

Figure 9. Cost Assumptions for LTE-U/LAA 'Cost per GB' Calculation

CBRS Small Cell		
Element	**Cost estimate**	**Notes**
Spectrum cost	$200	Estimated $0.50/MHz-pop for PAL license. Assuming changes to PAL licensing for longer term use
Radio equipment	$2,500	CBRS small cell; 5-year depreciation
Site lease	$100/month	avg. cost of muni pole attach cost in top US markets
Backhaul	$400/month	2-strand dark fiber cost or high-capacity lit service
Power	$4/month	Based on 20-50W base station power consumption
Effective Cell capacity	475 GB/month	Max. cell capacity with 5% average monthly utilization rate

Source: Mobile Experts

Figure 10. Cost Assumptions for CBRS 'Cost per GB' Calculation

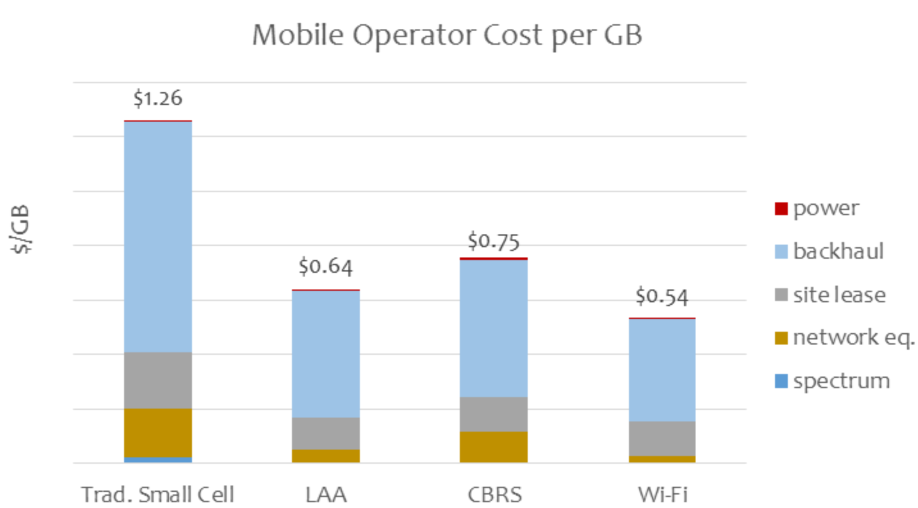
Carrier Wi-Fi		
Element	**Cost estimate**	**Notes**
Spectrum cost	$ 0	
Radio equipment	$1,000	Outdoor Wi-Fi unit; 5-year depreciation
Site lease	$100/month	avg. cost of muni pole attach cost in top US markets
Backhaul	$300/month	High-capacity ethernet link cost
Power	$3/month	Lower power consumption on Wi-Fi units
Effective Cell capacity	791 GB/month	Max. cell capacity with 5% average monthly utilization rate (larger footprint for high outdoor EIRP than LAA)

Source: Mobile Experts

Figure 11. Cost Assumptions for Carrier Wi-Fi 'Cost per GB' Calculation

Mobile Operator Perspective on Cost Analysis

A mobile operator can cut the cost of each GB of data almost in half, by leveraging unlicensed technologies. While the unit cost of delivering data over Wi-Fi is cheaper than LAA or CBRS, Carrier Wi-Fi has not proven to be an effective solution in a Wi-Fi offload setting, with operators left unhappy with Wi-Fi quality. Moreover, managing separate LTE and Wi-Fi networks have proven to be cumbersome and operationally inefficient. Taking these less tangible factors into account, the total cost of ownership for Wi-Fi may be higher than the simple unit costs as outlined in the figure below.



Notes: 1) Assume that a mobile operator would 100% lease backhaul;
2) In case the operator uses owned fiber/fixed network for backhaul, the unit costs can significantly decrease

Source: Mobile Experts

Figure 12. Mobile Operator's Unit Cost of LAA vs. CBRS vs. Wi-Fi

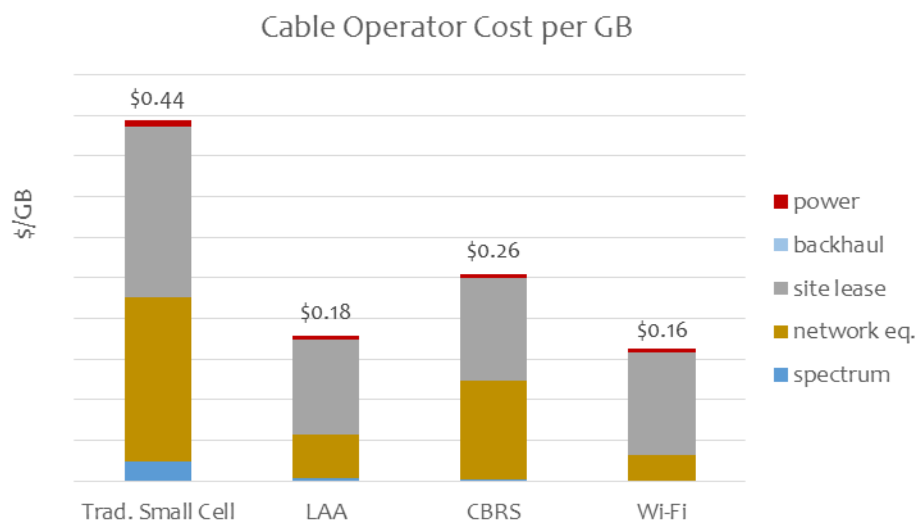
Cable / Fixed Operator Perspective on Cost Analysis

Carrier Wi-Fi has been the primary choice of cable operators over the past 10 years. They have built out tens of millions of public hotspots and homespots to complement their fixed broadband networks. To extend the wireless reach of fixed broadband services, cable operators have been placing outdoor Wi-Fi access points mounted on cable strands, and on street furniture. Although they seem committed to the outdoor Wi-Fi strategy for now, and publicly sing the praises of Wi-Fi, in private most cable executives will admit that LTE works better.

Cable and fixed operators now seem eager to run LTE on unlicensed and shared bands along with Wi-Fi. Mobile Experts believes that cable operators will begin deploying CBRS radios in 2018-2019 to take advantage of the new CBRS spectrum coming to market. There are two key perspectives here:

- The wireless services on CBRS networks may be viewed as "cable wireless" extension beyond the 5GHz band, with high quality, longer range than 5 GHz, and capacity beyond their Carrier Wi-Fi service.
- CBRS allows the cable operator to offload their outdoor traffic, which would normally be carried by a competing mobile operator under an expensive MVNO agreement.

For the cable operators, the baseline cost to deliver a GB of data is lower than the baseline for mobile operators. For cable operators who can leverage owned fiber and DOCSIS networks for backhaul, the unit cost per GB can be almost one-third that of a mobile operator leasing backhaul. In the end, wireless service is about transporting bits. Having internally-owned network infrastructure for backhaul provides tremendous advantages in wireless services as well, especially when one can leverage less expensive unlicensed or shared spectrum.



Notes: 1) Assume that a cable operator would use own fiber or DOCSIS as backhaul;
2) Although a cable operator can theoretically deploy licensed small cells, upfront spectrum cost can be too prohibitive

Source: Mobile Experts

Figure 13. Cable Operator's Unit Cost of LAA vs. CBRS vs. Wi-Fi

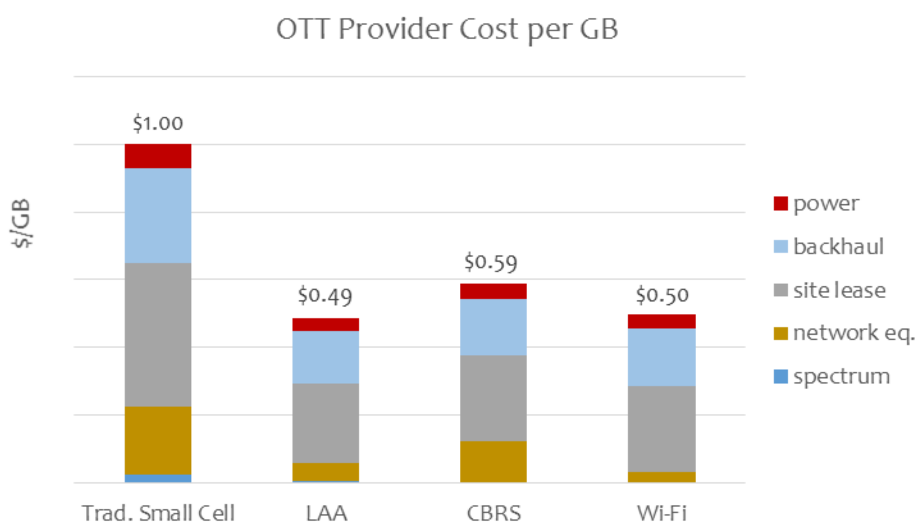
The cable operators view public Wi-Fi hotspots as a strategic asset in their pursuit of mobile wireless entry. In pursuit of this strategy, they appear inclined to continue making investments in public hotspots through outdoor deployments and public access via Wi-Fi enabled broadband CPEs. Using strategically placed hotspots as a foundation of their wireless footprint, cable operators have been experimenting with various business models ranging from wholesale access to retail wireless services.

Comcast's (and soon Charter's) MVNO business launches should be viewed only as a way to stitch together their unlicensed wireless networks. As an MVNO, they are incentivized to offload subscribers' traffic onto owned infrastructure to lessen the MVNO rent fees to a host mobile operator. It is possible for the cable operators to pursue LAA and LWA (through license acquisition or lease), but Mobile Experts believes that CBRS is a more likely path for the cable operators for now as it offers less onerous upfront spectrum cost to build up a LTE network.

Over-the-Top / Neutral Host Service Provider Perspectives

Independent "neutral" players like Boingo have been providing public wireless service over the unlicensed bands for many years. These providers have focused on strategic public venues like airports to establish a wireless footprint using Wi-Fi. They have typically charged for roaming access to mobile operators or other service providers and per-use fee to retail customers. A good example of a wholesale business model is the Wi-Fi roaming agreement that Boingo has established with Sprint. Under this agreement, Sprint customers can automatically roam onto Boingo's Wi-Fi networks at major US airports and use the networks as if they are on Sprint's network coverage. With Hotspot 2.0 profiles pre-installed on Sprint phones, Sprint customers can seamlessly access Boingo's Wi-Fi network without the typical Wi-Fi login process. This has worked quite well for Sprint. Other operators—with Verizon as the prime example—are less happy about the quality of these in-building Wi-Fi networks and have chosen not to participate in Hotspot 2.0 offload opportunities. So, a segment of the mobile community wants to retain control over QoS.

Although its unit cost is slightly higher than Wi-Fi, mainly due to the SAS burdened cost embedded in the network equipment cost, CBRS offers an inexpensive means to reach a higher level of quality with LTE. Without high upfront costs for spectrum, OTT and neutral host providers can selectively build out CBRS network to serve specific market needs. For example, a neutral host provider can build in-building wireless system based on CBRS small cells to offer LTE network services to enterprises directly or through mobile operators. Assuming that future smartphones distributed through mobile operator channels support CBRS, OTT service providers can potentially offer much more cost-effective in-building wireless solutions than traditional DAS solutions.



Notes: 1) Assume WiGig PTP 60GHz radio deployment for small cell backhaul to lessen the backhaul cost;
2) Assume that WiGig PTP radio gear has a 5-year lifespan;
3) Although an OTT operator can theoretically deploy licensed small cells, upfront spectrum cost is too prohibitive to be realistic (for reference only)

Source: Mobile Experts

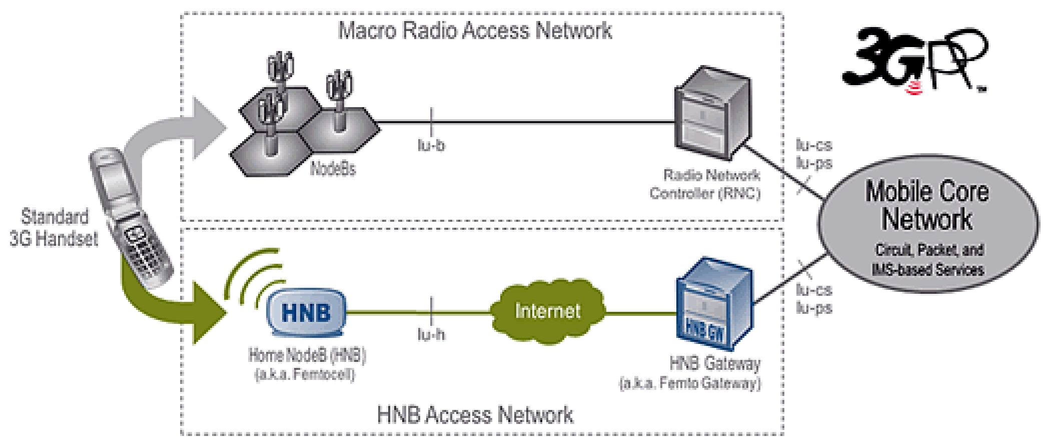
Figure 14. OTT Operator's Unit Cost of LAA vs. CBRS vs. Wi-Fi

4 Technology Background

For the CBRS market, the small cell architecture will generally be used in all use cases, due to the radio power restrictions imposed by the FCC. Fortunately, the small cell architecture is well established and proven in the field at this point, so the new elements in a CBRS network are related to spectrum sharing.

Small Cells

Mobile Experts defines small cells as self-contained radio nodes which include all Layer1-3 baseband processing for licensed mobile communications. Small cells use a highly integrated RAN structure with nodeB and RNC functionality or base station and base station controller collapsed in an integrated design. One variation on this theme: some small cell units (such as Commscope/Airvana and Spidercloud enterprise small cells) are broken up into two physical boxes within the building, where some Layer 1/Layer 2 baseband processing is executed in the radio unit and the rest of Layer 2/Layer 3 processing is done in a controller box for multiple radio units. Where this split is achieved locally within the building, we still consider the unit to be a "small cell" and not a Remote Radio Head.

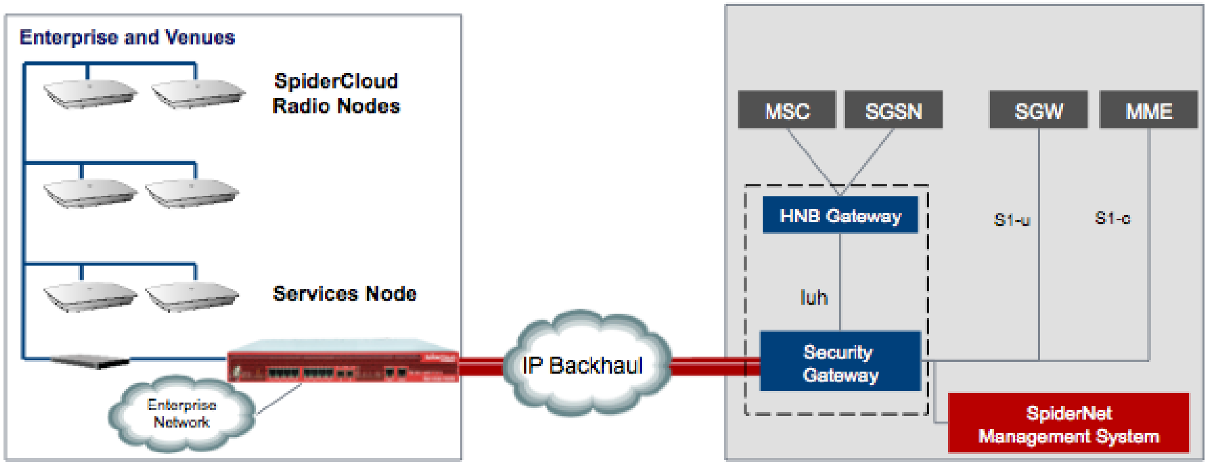


Source: 3GPP

Figure 15. Femtocell and Gateway architecture diagram

Controller-based Small Cell Architectures

Enterprise applications increasingly use a local controller to coordinate multiple small cells, to assist in local breakout, caching of local data, integration with the company's server or LAN, and to facilitate LTE-Advanced features such as CoMP and eICIC. This approach facilitates deployment of the radio units throughout the building very quickly, because the controller box in the IT closet feeds Cat-5 or Cat-6 cabling which can be deployed very quickly over the ceiling tiles in many office buildings.



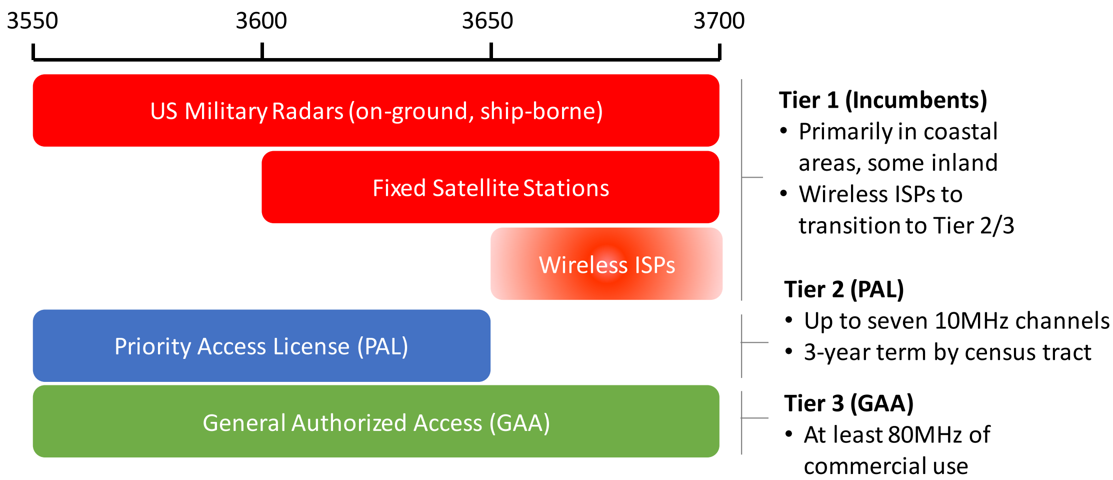
Source: Spidercloud

Figure 16. An example of a controller-based architecture for small cells

The controller-based approach works best for larger buildings, where multiple radio nodes are deployed that may overlap with each other and where some coordination between radio nodes is important. Over time, we expect the controller box to become a platform for the enterprise to run value-added services such as instant messaging or other applications for employees throughout the building.

CBRS Basics

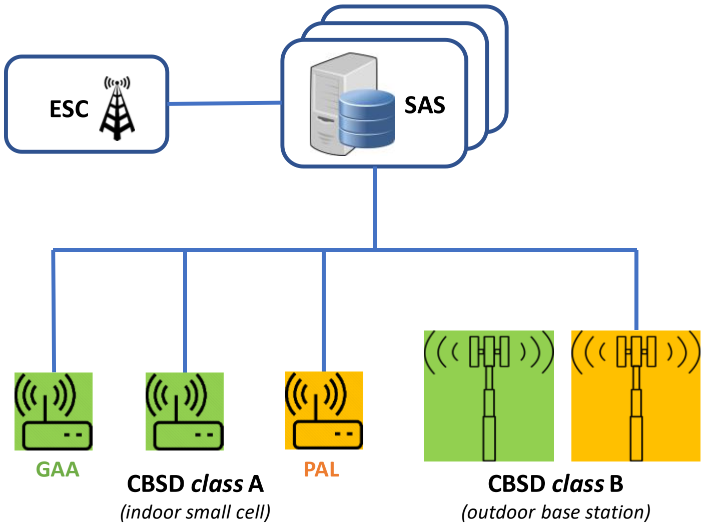
In 2015, the U.S. Federal Communications Commission (FCC) formally established *Citizen Broadband Radio Service* (CBRS) for shared commercial use of the 3.5 GHz (3550-3700 MHz) band with the incumbent military radars and fixed satellite stations. For the first time, dynamic spectrum sharing rules have been defined to make additional spectrum available for flexible wireless broadband use while ensuring interference protection and uninterrupted use by the incumbent users. Under the plan, a three-tier sharing paradigm coordinates spectrum access among the incumbent military radars and satellite ground stations and new commercial users. The three tiers are: *Incumbent*, *Priority Access License* (PAL), and *General Authorized Access* (GAA) users.



Source: Mobile Experts

Figure 17. CBRS Three-Tier (Shared Spectrum) Licensing Structure

A key element of the CBRS spectrum sharing architecture is the *Spectrum Access System* (SAS). A SAS maintains a database of all CBRS base stations, formally referred to as *Citizens Broadband Radio Service Devices* (CBSDs), including their tier status, geographical location, and other pertinent information to coordinate channel assignments and manage potential interferences. To mitigate possible interference to tier 1 military radar systems, environmental sensors known as the *Environmental Sensing Capability* (ESC) are deployed in strategic locations near naval stations, mostly along coastal regions, to detect incumbent activities. When incumbent use is detected, the ESC alerts the SAS, which then directs CBSDs utilizing impacted CBRS channels in that area to move over to other channels. The cloud-based SAS enforces the three-tier spectrum sharing mechanism based on FCC rules via centralized, dynamic coordination of spectrum channel assignments across all CBRS base stations in a region.



Source: Mobile Experts

Figure 18. CBRS Functional Overview

The CBRS rulemaking defines two classes of base stations: *class A* and *class B*. A class A base station can be thought of as indoor or low power outdoor small cells with a maximum conducted power of 24 dBm (per 10 MHz) and maximum EIRP of 30 dBm (1 watt). This type of small cell is similar to "enterprise-class" small cells in the marketplace with 250mW transmit power with a typical 2 dBi omni antenna or up to 6 dBi directional antenna. Meanwhile, a class B base station is meant for outdoor use with a maximum EIRP of 47 dBm (50 watts). With a very high-gain antenna, outdoor CBRS base station can potentially be used for fixed wireless purposes. While indoor and outdoor base stations can be assigned to either GAA or PAL, we expect to see more indoor GAA deployments until ESC certification and PAL auctions get finalized.

The CBRS ecosystem is progressing along with FCC certification of SAS expected by end of 2017. While there is some uncertainty around possible CBRS rule changes around larger spectrum "parcel" size and licensing term extension from three to ten,[3] major operators are pushing ahead with CBRS radio deployment plans for 2018. The interests around CBRS deployment have heightened over the course of 2017. While the possible rule changes may impact a longer-term prospect of CBRS market, Mobile Experts believes that near-term deployment plans will push ahead as CBRS network deployments will likely aid cable operators' strategic leverage with mobile operators in MVNO negotiations and/or possible M&A discussions.

[3] CTIA and T-Mobile separately requested CBRS rule changes to FCC: http://www.fiercewireless.com/wireless/t-mobile-joins-ctia-pushing-fcc-to-reform-rules-for-3-5-ghz

Core Network Connectivity

Operators don't want to deal with setting up EPC connections to every new building and every neutral host that enters this market. At the same time, enterprises and some neutral hosts don't have the Rolodex to be able to coordinate with all of the operators' core networks. So, there is a new opportunity here for a "clearinghouse" or aggregator to take a role in authenticating and setting policy for the operators, in the case of in-building CBRS connections.

Connection to the core networks are key because each handset that enters the building must be authenticated (to prove that this is a valid user), and other policy and control functions specified by the operators should be enforced to ensure the most consistent user experience possible compared with the outdoor macro network.

Individual connections to each service provider's EPC would be duplicative and inefficient. We expect this market to quickly move to a few key aggregators, likely led by some of the leading SAS providers.

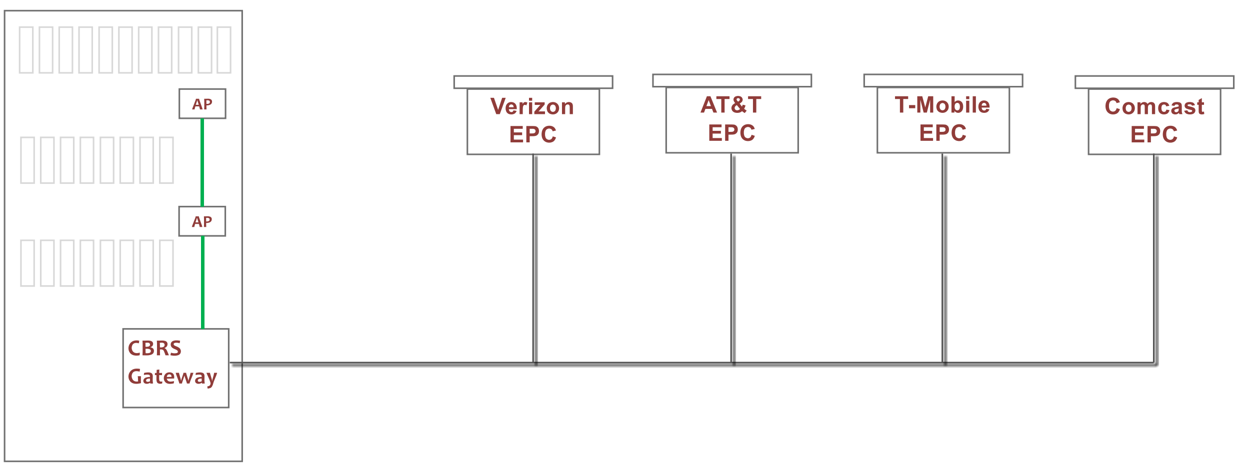


Figure 19 Direct connections to each operator's core network

Sources: Mobile Experts

Managed services through a neutral host network (NHN) provider requires integration of core networks between the NHN and multiple network operators as shown below. The interworking between NHN and multiple operators can leverage the WLAN internetworking architecture as defined in 3GPP. A mobile device can use ePDG to gain access to an operator's IP services, including voice services over IMS. The service continuity is maintained between NHN and an operator network, and local IP services (e.g., enterprise PBX) can be provided through local breakout at the neutral host network. Another key aspect of the NHN core network is to provide key performing indicators (KPIs) or charging metrics to operator's core network through NHN EPC. Since the NHN in this case needs to meet the CBRS governing rules, the NHN core also needs to interface with SAS for dynamic channel assignments through the C BRS Gateway as necessary.

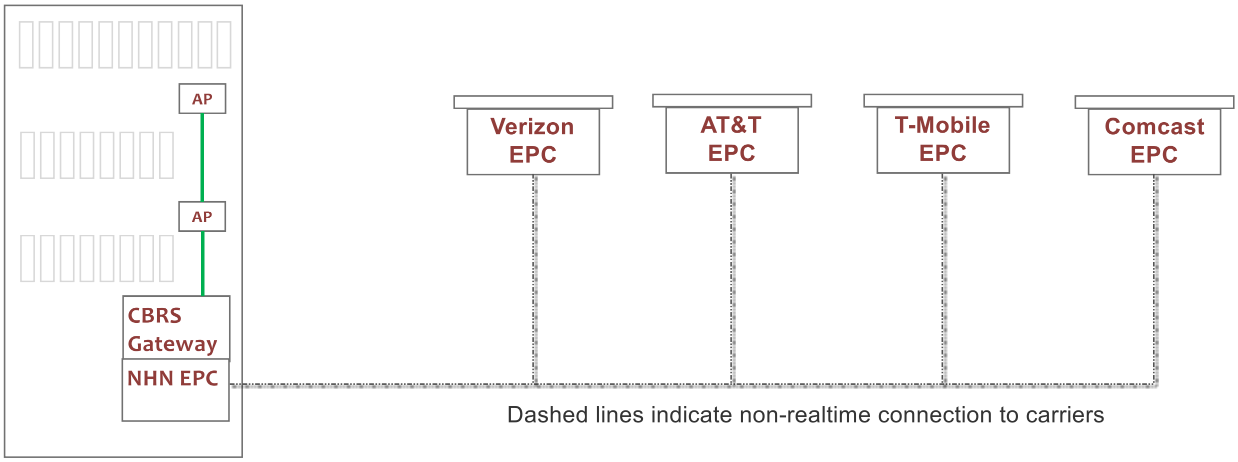


Figure 20 Aggregation of core network authentication and policy by a neutral host EPC

Sources: Mobile Experts

Client Devices

It's important to keep in mind that the USA is not a big enough market to drive instant acceptance of a new feature such as CBRS into global smartphone platforms. Apple and Samsung's Galaxy team are currently considering how to implement the 3.5 GHz band into handsets, and their choices are complicated by a variety of LTE, 5G, and CBRS plans that range from 3.3 GHz to 4.2 GHz.

There are two choices for implementation of filters for CBRS, LTE, and 5G services between 3.3 and 4.2 GHz.

1. The obvious first choice for simplicity is to use a single bandpass filter, covering the entire band from 3.3 to 4.2 GHz.

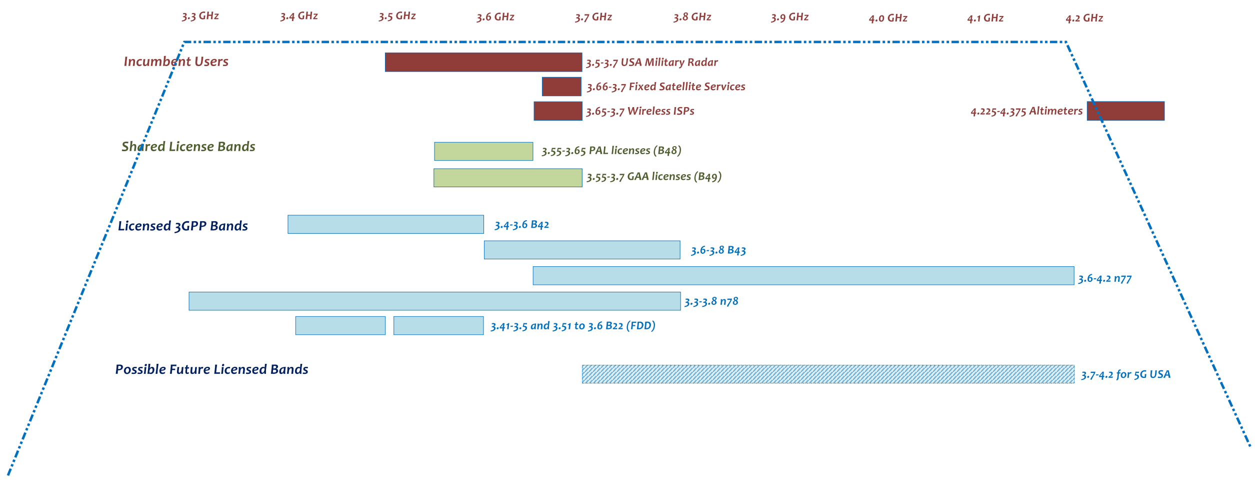


Figure 21 A single-filter implementation at 3.3 to 4.2 GHz

Sources: Mobile Experts

This would be a fairly low cost approach due to the limited number of filter/PA combinations involved. However, the drawbacks would include poor PA efficiency due to the wide band covered (24% bandwidth), and shallow rejection skirts due to the wide bandwidth of the filter. Rejection of the altimeter and adjacent radar systems would be weak.

2. A second choice involves splitting the 3.3-4.2 GHz band into two slices, such as 3.3-3.8 GHz (known as n78 for 5G NR discussion within 3GPP) and for other apps at 3.6-4.2 GHz. In this arrangement, each regional use case would be covered by one of the filters. Note that the most likely implementation would be as a single Complete Front End (aka PAMiD) module that covers multiple bands and multiple PA paths, so that each of these two filters would have a narrowband power amplifier supporting it, for higher efficiency performance.

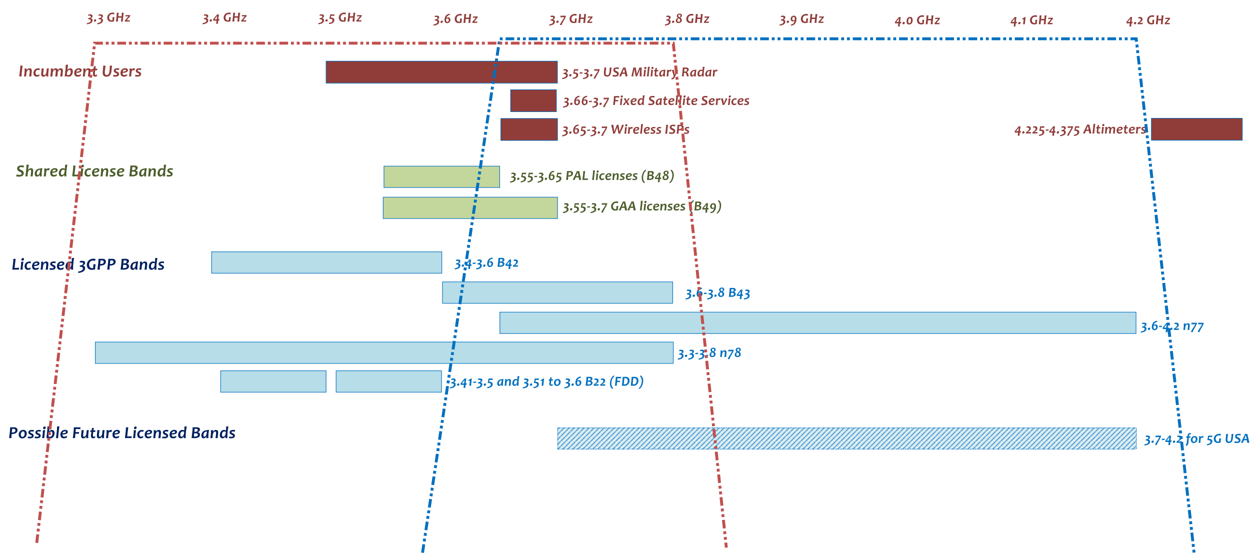


Figure 22   A dual-filter implementation at 3.3 to 4.2 GHz

Source: Mobile Experts

Overall, we believe that the second option is preferable, with better protection from out-of-band radar and altimeter systems and higher efficiency, with only a small increase in cost.

With regards to commercial timing, we currently see implementation of 3GPP Band 42 filters in a few smartphones in Japan (covering up to 3600 MHz), and there's some development underway with second-tier handset manufacturers for handsets to cover 3550-3700 MHz for the 2018-2019 early deployments.   However, Apple and Samsung have not yet issued any firm specifications for filters to cover the 3400-4200 MHz bands.

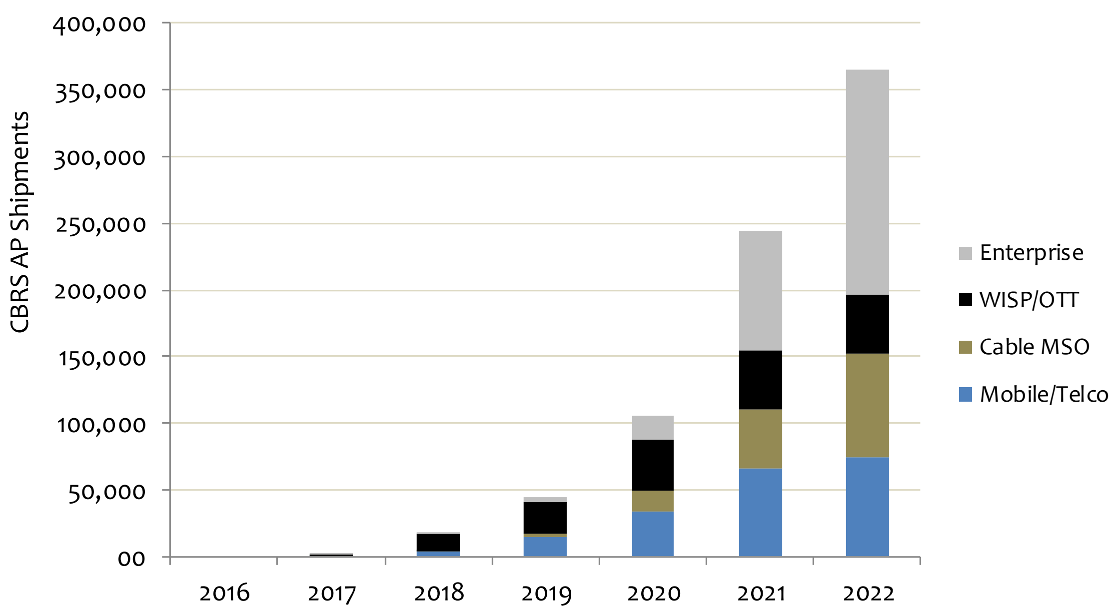
During 2019, we expect Google/Pixel, LG, and a few other second-tier handset vendors to have options available.   We predict that major global smartphone platforms will start with Samsung's regional smartphones for the US market, then followed by a worldwide Galaxy class handset in 2019. Apple is not likely to support the full CBRS band until late 2019 to 2020.   In summary, we don't expect the penetration of CBRS in American handsets to reach critical mass of 30% or higher until 2021 or later.

5 CBRS Outlook

Unlicensed LTE is still in its infancy, but multiple driving forces will combine to create growth over the next five years. Market growth for 2017-2022 is likely to weigh in above 100%. A three-digit percentage growth rate is plausible due to the very low starting point, and a growth rate of about 46% from 2020 through 2022.

One key assumption in the forecast is that multiple service provider groups and some large enterprises will participate based on the innovative licensing rules. If the CBRS licensing rules were to be changed in favor of incumbent mobile operators with higher spectrum costs and other onerous use terms, expected participation from big operators could increase, with a possible decrease in regional enterprise use.

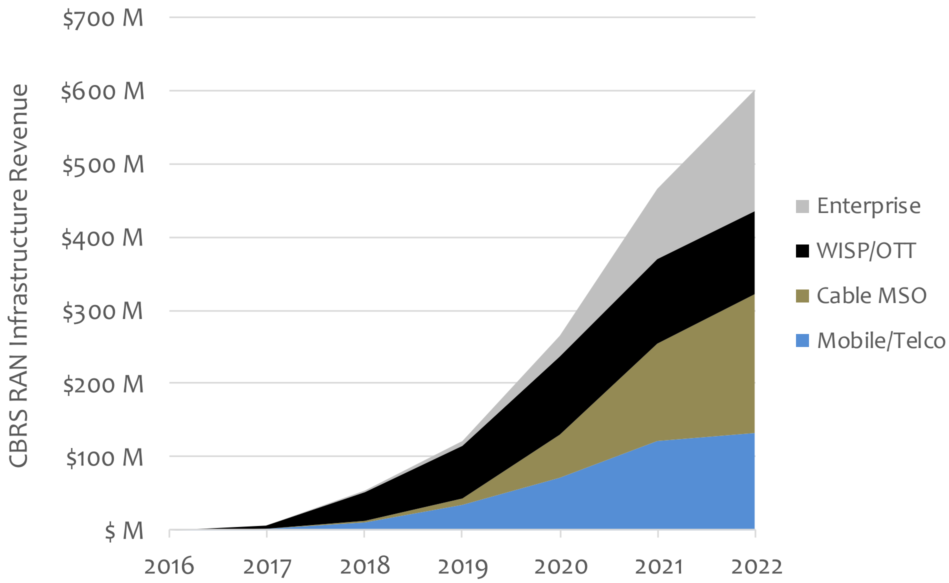
Mobile operators and cable operators will both invest in CBRS small cells. WISPs are already investing, with a few early adopters taking advantage of very early infrastructure. And enterprises will pick up in the 2020-2022 timeframe as Private LTE networks start to become easy enough for enterprises to use.



Source: Mobile Experts

Chart 2: CBRS Small Cell Shipments, by business model, 2016-2022

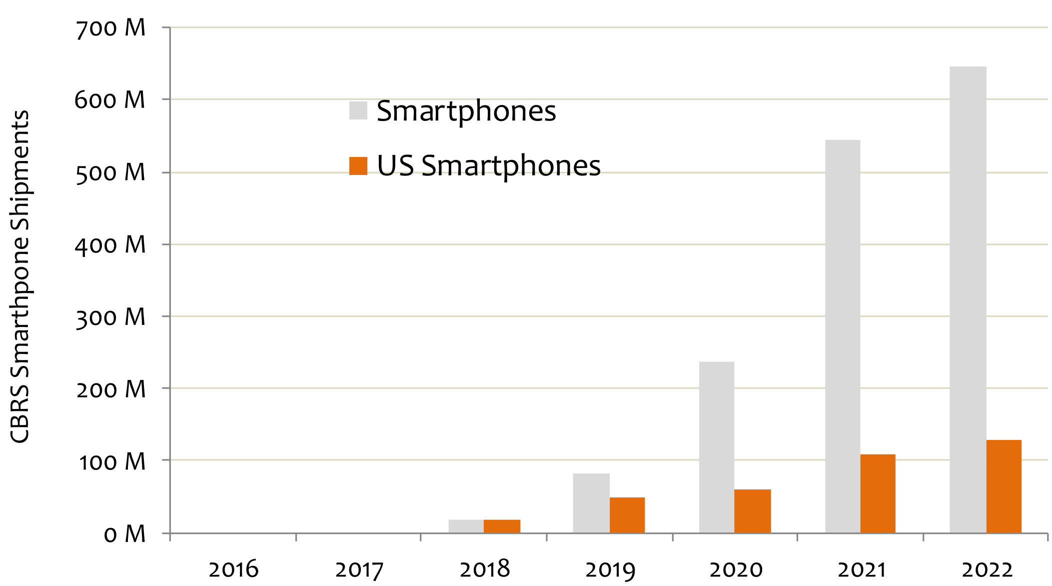
Revenue for CBRS infrastructure will also grow quickly. The early implementation by FWA service providers and WISPs will result in a lot of outdoor access point deployment, with high ASPs in the first few years. We expect revenue to reach about $500M for CBRS RAN infrastructure within 5 years.



Source: Mobile Experts

Chart 3: CBRS Small Cell Revenue, by business model, 2016-2022

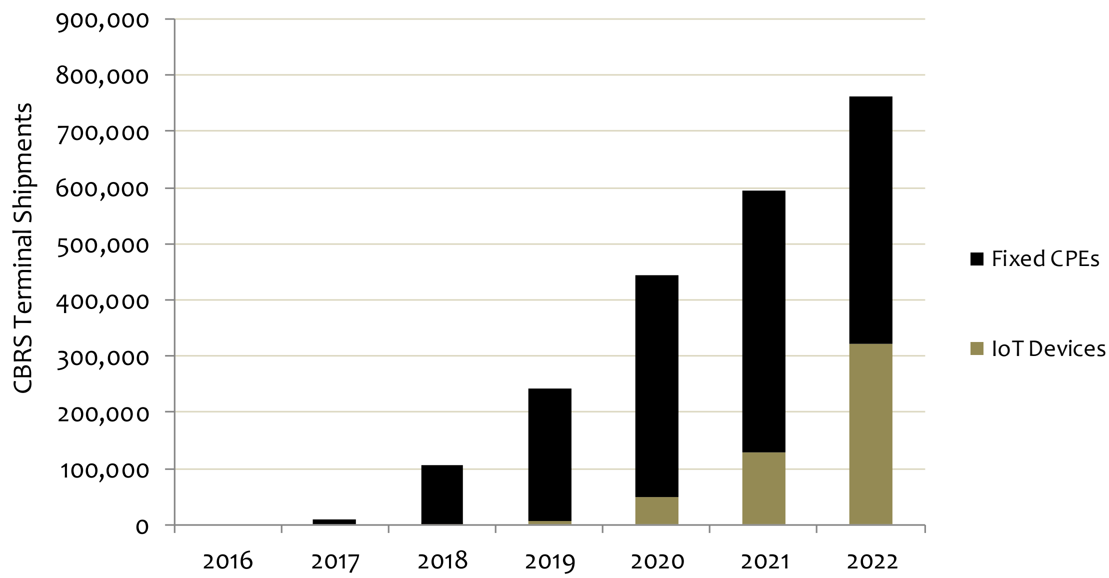
With CBRS, three different types of terminals will be used. Of course, smartphones will be modified to work on the CBRS frequency band for general LTE access….so even modest adoption in the smartphone market results in hundreds of millions of UEs worldwide, with over 100 million sold per year by 2021. In other words, practically every LTE handset in the USA will include CBRS by 2022.



Source: Mobile Experts

Chart 4: CBRS Smartphone Shipments, 2016-2022

Non-handset terminals will also grow quickly. IoT devices will be used in Private LTE networks, growing to hundreds of thousands of devices per year by 2022. Finally, CBRS fixed wireless access will involve hundreds of thousands of CPEs (customer premise equipment solutions) to enable FWA services.



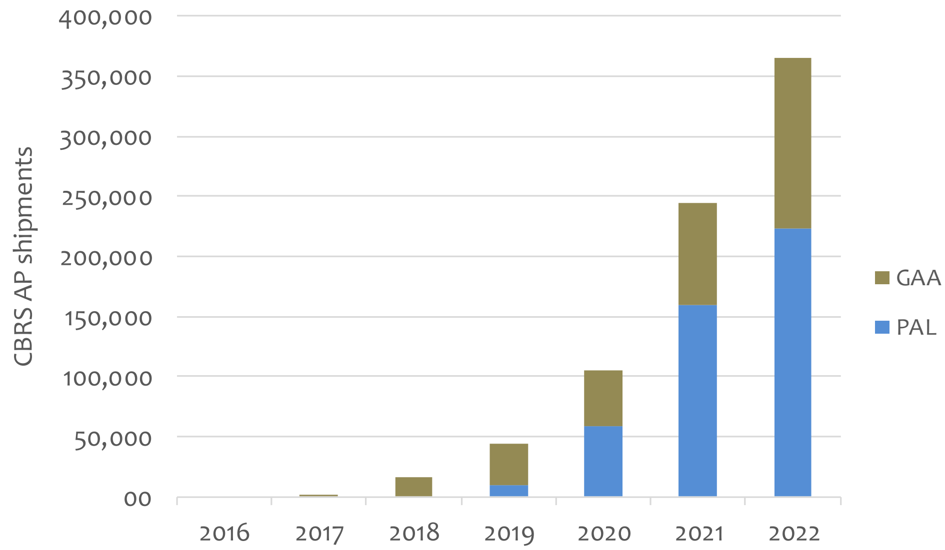
Source: Mobile Experts

Chart 5: CBRS CPE and IoT Device Shipments, 2016-2022

CBRS RAN Equipment Forecast

Most mobile and cable operators have a strong preference for use of the PAL licenses if possible, because the PAL licensing arrangement will work almost as well as fully licensed spectrum for most areas of the country. GAA licenses carry the unknown quality that a PAL user can interrupt communications, so the big mobile operators will especially prefer PAL.

Because the licensing terms are still in flux and may change from non-renewable 3 year terms to longer 10 year, renewable terms, our predictions for PAL and GAA deployment can be only tentative at this time. The below chart reflects our assumption that the license terms will be changed to accommodate longer terms, larger areas, and renewability.

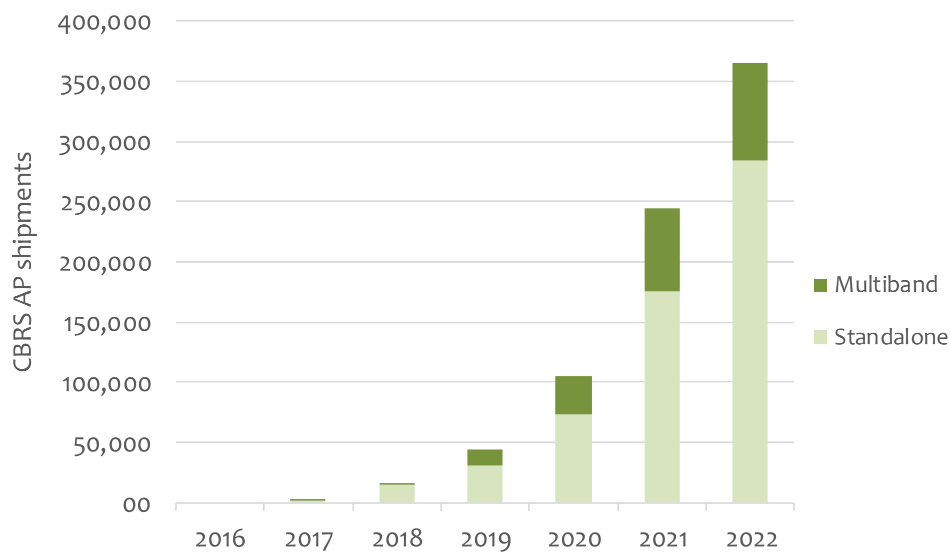


Source: Mobile Experts

Chart 6: CBRS Small Cell Shipment Forecast by License Type, 2016-2022

Mobile Experts expects the mobile operators to deploy CBRS multiband small cells, meaning that CBRS will be used along with a licensed LTE band with Carrier Aggregation. In this way, the operators will be able to leverage the shared spectrum band in LAA fashion - i.e., aggregate carriers across both shared and licensed spectrum bands to increase capacity and enhance user throughput. Cable operators and Private LTE, on the other hand, will use control channels in the CBRS band, with the possibility of Carrier Aggregation/LAA on the 5GHz unlicensed band. For simplicity, we count the Cable MSO deployments as "Stand alone" despite this possibility.

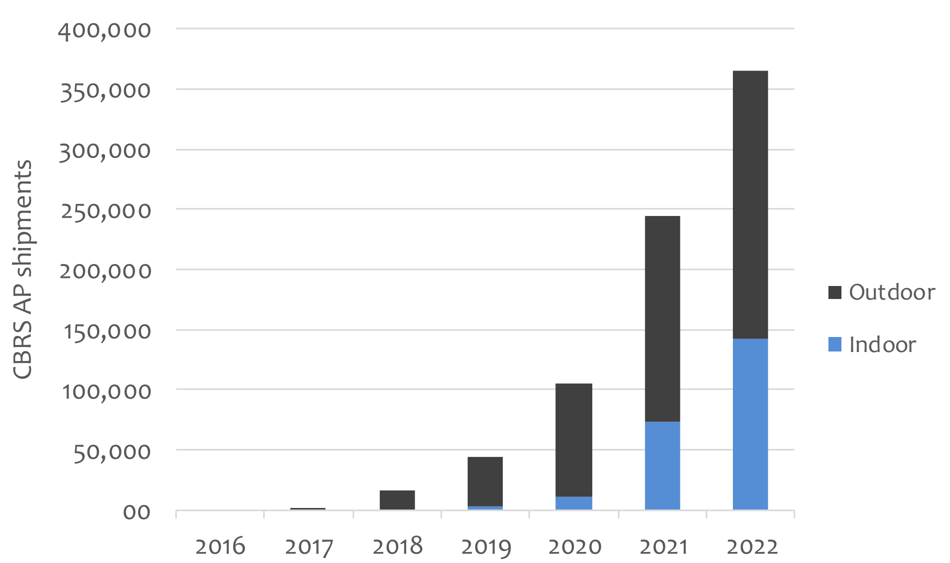
In the near term (2018-2019), Mobile Experts forecasts the cable operators to be more aggressive in both outdoor and indoor deployments, so the "Standalone" category dominates the picture. By the end of the forecast period, Mobile Experts forecasts the mobile operators to deploy about 45% of all CBRS radios as multiband small cells. Cable operators are expected to deploy about 20% of all CBRS radios as standalone small cells in 2022. Moreover, large "tech-savvy" enterprises and some neutral host providers are also likely to deploy about 15-17% of all CBRS radios in 2022 to take advantage of new CBRS spectrum band for enterprise applications that require greater service quality.



Source: Mobile Experts

Chart 7: CBRS Small Cell Shipment Forecast by Multiband vs Standalone, 2016-2022

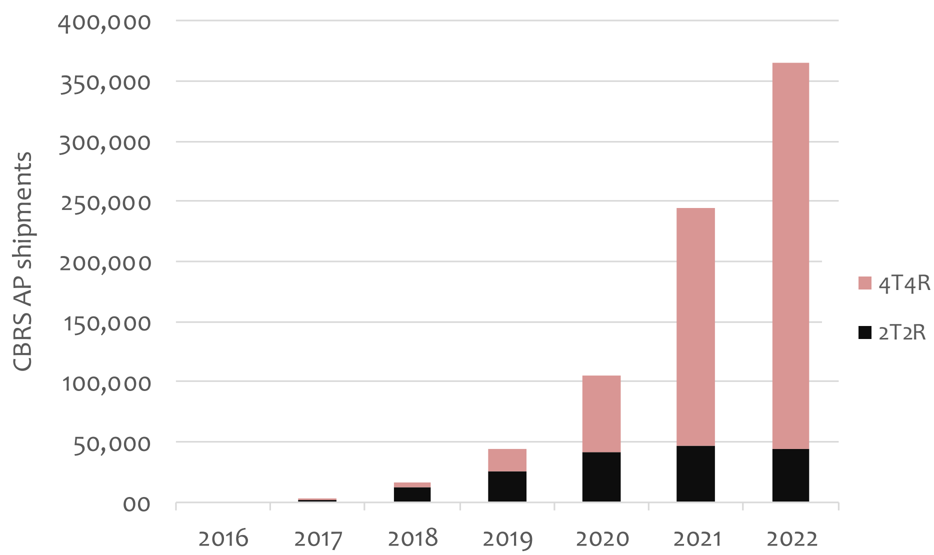
Both mobile and cable operators are likely to make heavy use of outdoor CBRS access points. Fixed wireless and WISP implementation will domoinate the market in the early days, from 2017 through about 2020. As Private LTE systems heat up in the enterprise market in 2020-2022 timeframe, we will see a lot more indoor CBRS small cells coming in to the market.



Source: Mobile Experts

Chart 8: CBRS Small Cell Shipment Forecast by Indoor vs Outdoor, 2016-2022

In the early days of the market, CBRS is considered a coverage solution, so 2x2 MIMO is currently designed into a lot of the early small cell products. Over time, we expect that 4x4 MIMO will be used, especially as 5G handsets emerge with 4x4 capability in the 3.5 GHz band. 5G operation in that band will drive 4x4 hardware implementation, so we expect smartphones to support CBRS with 4x4 as well. The clear trend over the longer term will be toward 4x4 small cell infrastructure.



Source: Mobile Experts

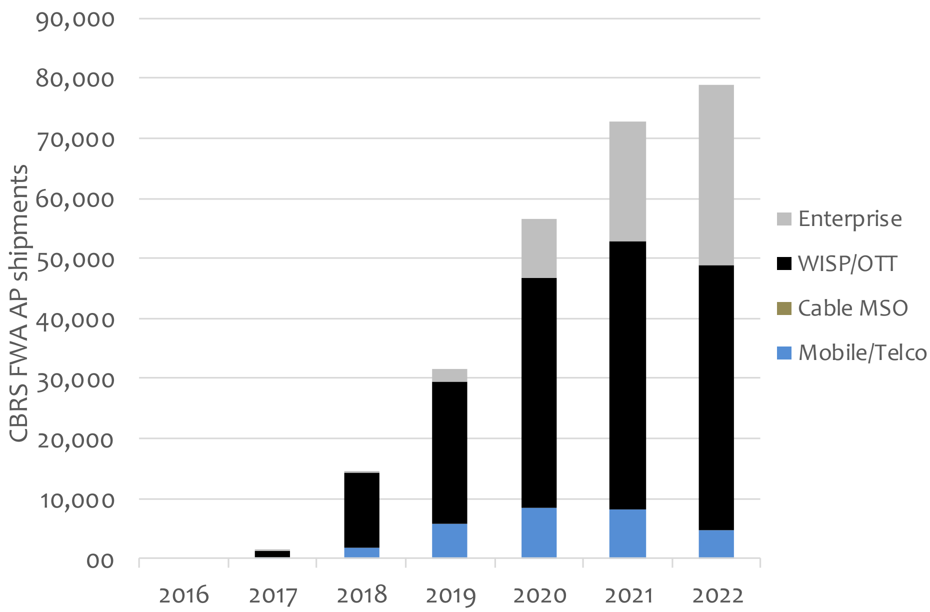
Chart 9: CBRS Small Cell Shipment Forecast by MIMO order, 2016-2022

CBRS Fixed Wireless Access Forecast

The CBRS spectrum is a great fit for the Fixed Wireless Access application, with long range, good penetration of foliage, and inexpensive access to spectrum, especially in rural areas. Early adopters such as Paladin Wireless and Cal.net are already moving forward, despite the lack of maturity in the spectrum and solutions. Mobile Experts estimates that WISPs have an installed base currently of about 170,000 Wi-Fi or WiMAX based FWA sites, and based on steady replacement of these legacy solutions with superior CBRS radios we expect a surge of deployment over the next 4-6 years.

The current forecast assumes that FWA service providers will replace their existing installed base in a wave of deployment, so operator-driven FWA deployment would slow down after the initial surge. It's also possible that new subscribers will join the FWA service due to higher quality or faster Internet service, but we have conservatively forecasted slow growth in this regard.

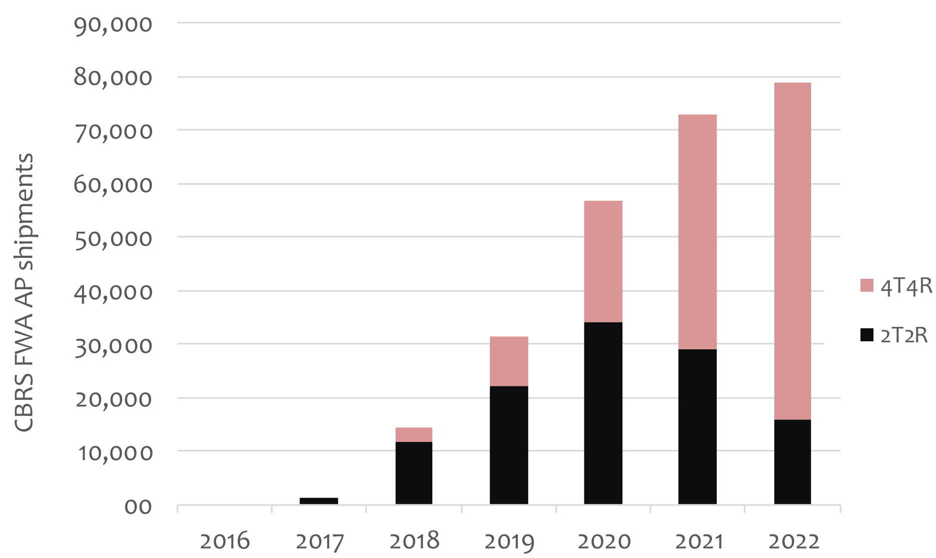
Private LTE systems for fixed access can include security cameras and other fixed assets. We expect this type of deployment to catch on during the 2020-2022 timeframe, and represents a possibly large market in the longer term.



Source: Mobile Experts

Chart 10: CBRS FWA shipment forecast, by operator type, 2016-2022

Most fixed-wireless CBRS small cells will use 2x2 MIMO at first, but we expect these to quickly migrate to 4x4 MIMO because the CPEs are not contstrained by antenna size or similar considerations.



Source: Mobile Experts

Chart 11: CBRS FWA shipment forecast, by MIMO order, 2016-2022

Assuming that the PAL licensing rules are extended to 10 years and renewable, then we expect rural WISPs to invest in their regions. The cost to secure a PAL should not be so high, so we expect that 75% of WISP deployment will migrate to a PAL license. There will always be small mom+pop WISPs that see no need to pay for a PAL, so we have retained 25% of deployment in the GAA category.

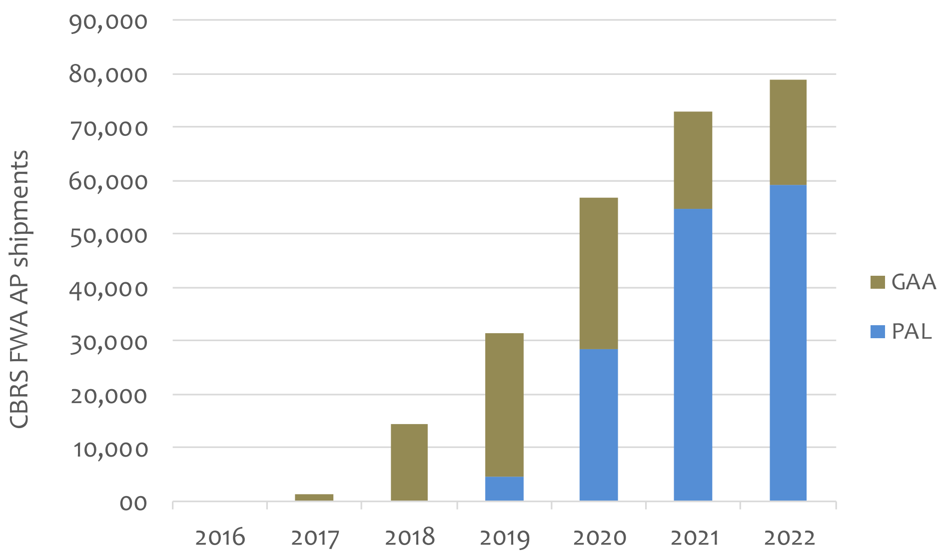
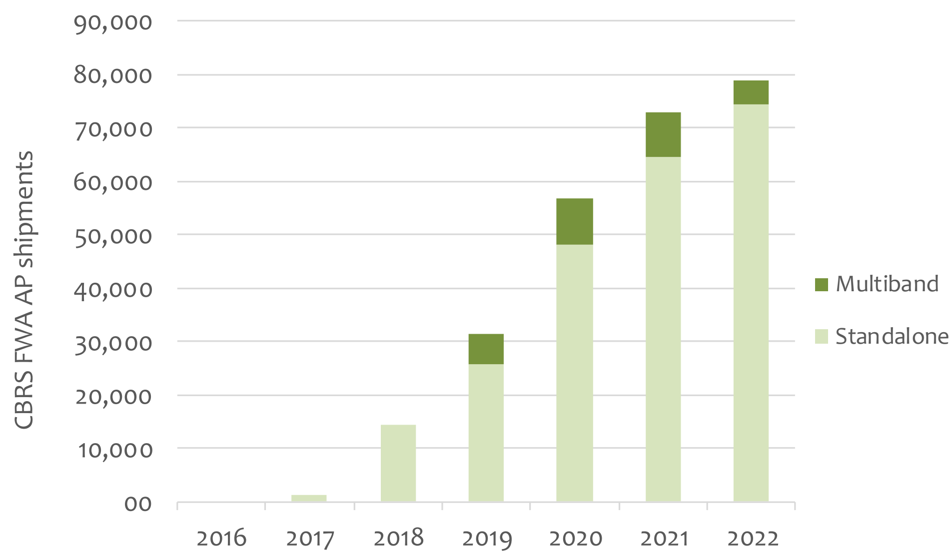


Chart 12: CBRS FWA shipment forecast, by GAA vs PAL, 2016-2022

Most FWA deployments will be stand-alone for WISPs and Private LTE deployment. Mobile operators deploying LTE for fixed wireless access may use some multi-band units but we expect simple solutions to dominate this market.

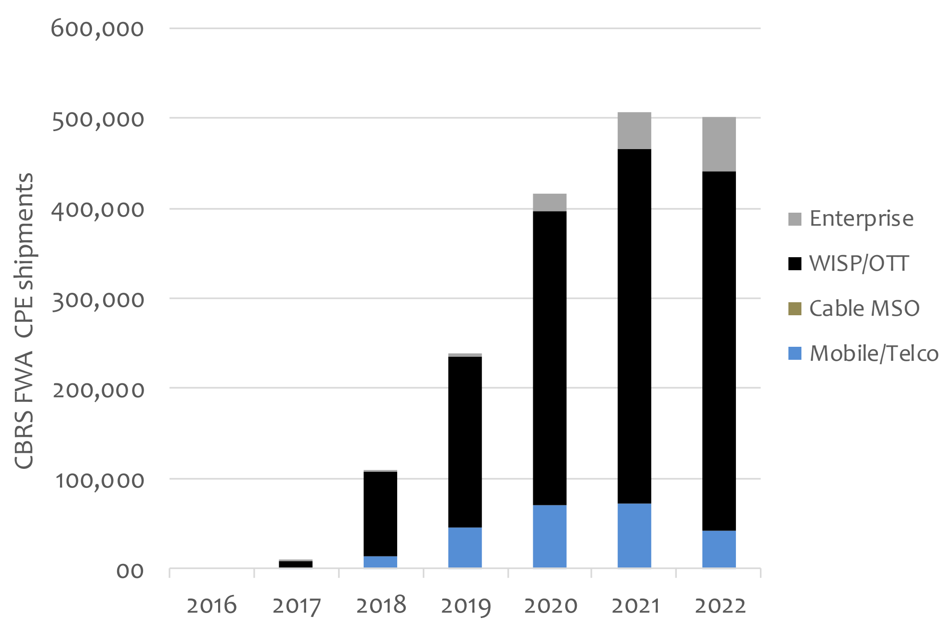


Source: Mobile Experts

Chart 13: CBRS FWA shipment forecast, Standalone and Multi-band, 2016-2022

CBRS Fixed Wireless Terminal Forecast

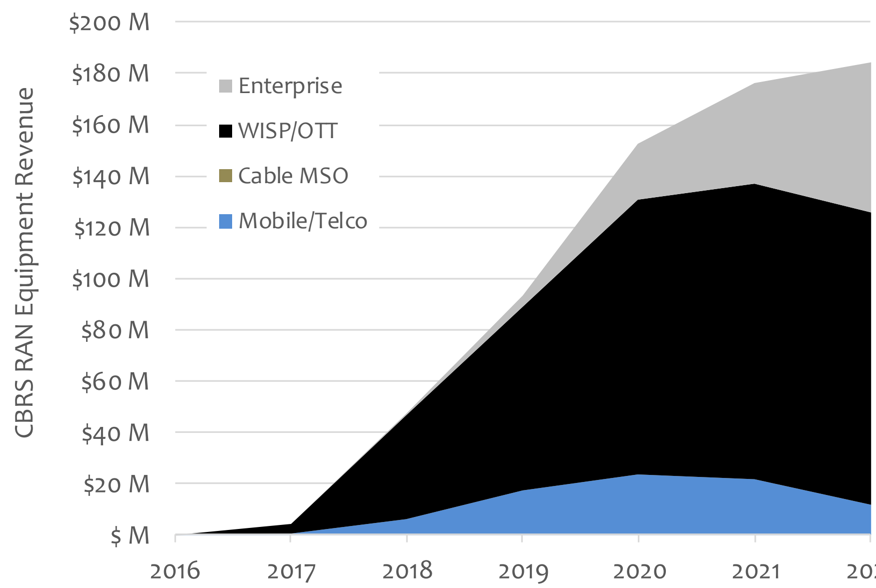
Customer Premise Equipment will need to be deployed at the same time as the FWA infrastructure at the hub, as WISPs and others will be converting from Wi-Fi or WiMAX to CBRS. As a result, the CPE forecast closely mirrors the infrastructure forecast.



Source: Mobile Experts

Chart 14: CBRS FWA CPE shipment forecast, by operator type, 2016-2022

In Fixed Wireless Access, the revenue associated with RAN infrastructure (including both FWA hubs and the CPEs) will total more than $70M within two years.   The rapid adoption by WISPs that are dissatisfied with Wi-Fi will be responsible for a quick rise in revenue here.



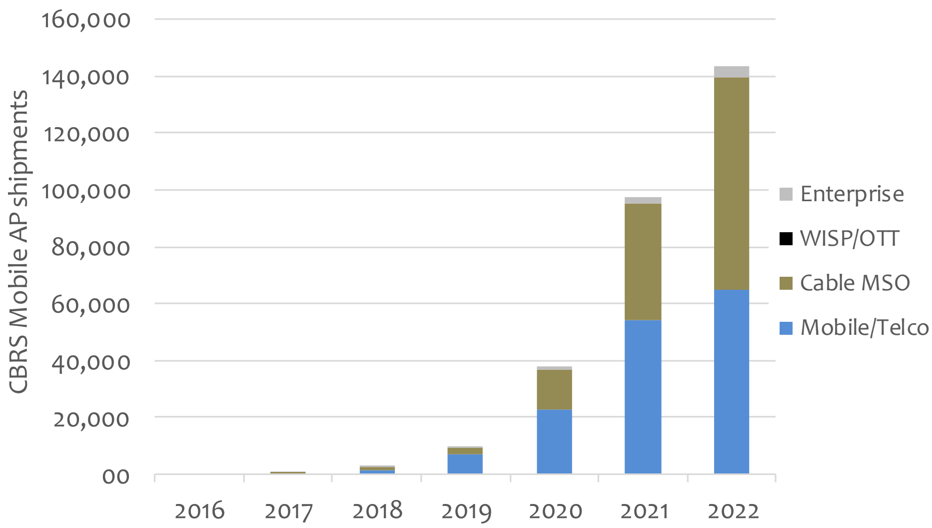
Source: Mobile Experts

Chart 15:   CBRS FWA RAN equipment forecast, by operator type, 2016-2022

CBRS Mobile Access Forecast

Deployment of CBRS equipment by mobile operators and cable operators in an outdoor setting will be intended for mobile use….in other words, the terminals will be moving around.   We can expect that for the mobile operators, handovers to adjacent cell sites and other control signaling will happen on another licensed band, but for cable operators the outdoor mobile deployment of CBRS presents a new challenge in setting up a true mobile network.

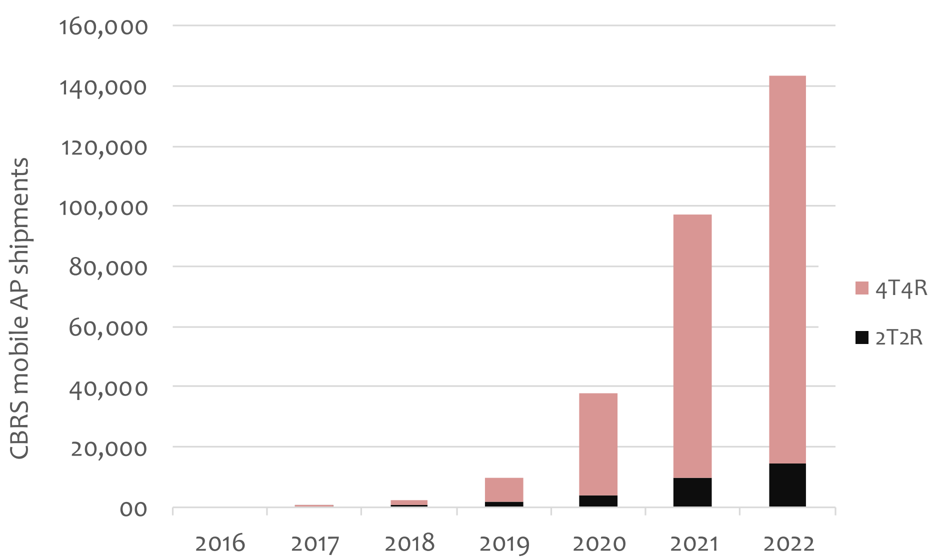
Private LTE deployment will also contribute to the mobile CBRS forecast, as autonomous and portable IoT devices will be used as well as smartphones for company employees.



Source: Mobile Experts

Chart 16: CBRS Mobile AP shipment forecast, by operator type, 2016-2022

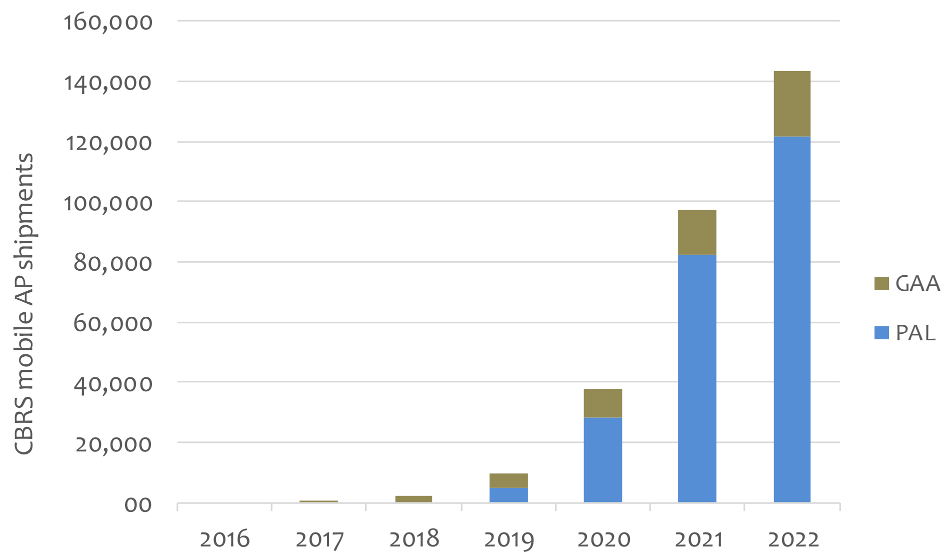
The technical configuration of mobile CBRS infrastructure will depend on the smartphones released to the market. We expect that most of these devices will support 4x4 MIMO, so almost all of the mobile CBRS small cells should also support 4x4 MIMO.



Source: Mobile Experts

Chart 17: CBRS Mobile AP shipment forecast, by MIMO order, 2016-2022

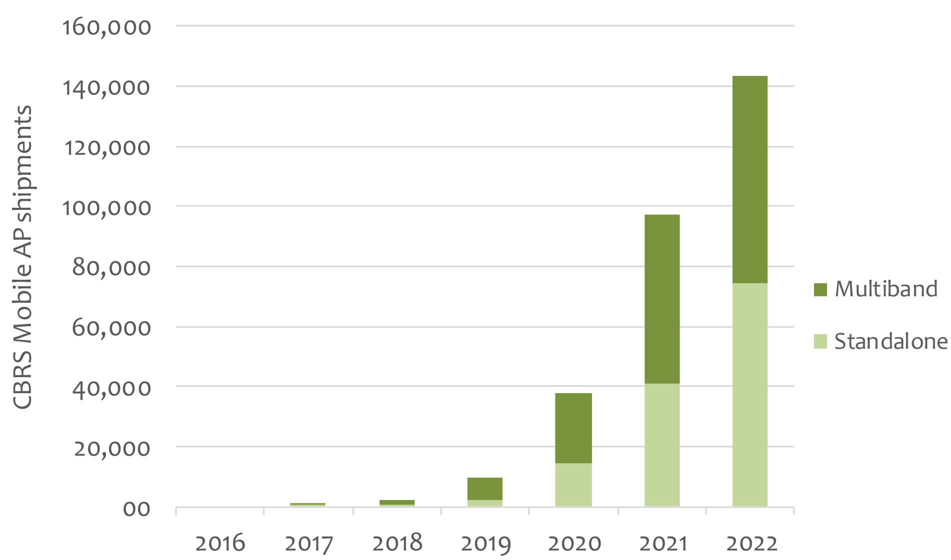
Because most of the mobile CBRS deployment will be carried out by mobile and cable operators, we expect them to show a strong preference for "reserving their seat" by acquiring a PAL license. The below chart assumes that PAL license terms will be changed for longer terms (10 years) and renewability.



Source: Mobile Experts

Chart 18: CBRS Mobile AP shipment forecast, by GAA vs PAL, 2016-2022

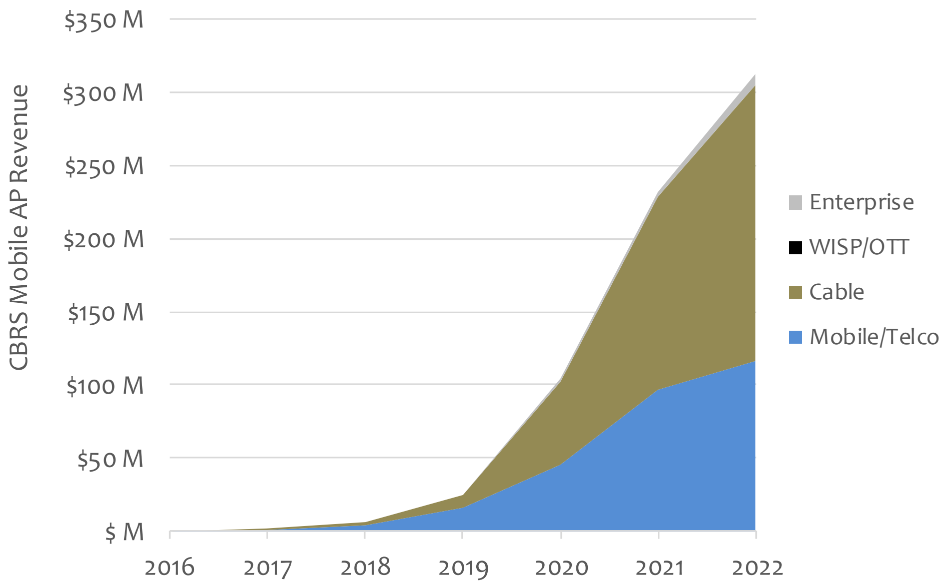
About half of the mobile CBRS deployment should be carried out by mobile operators, and the other half is likely to result from cable operators filling in their footprint. Because mobile operators will prefer multi-band small cells and cable operators are more likely to use single-band small cells, we anticipate a fairly evenly split market with regard to band support.



Source: Mobile Experts

Chart 19: CBRS Mobile AP shipment forecast, multiband vs. standalone, 2016-2022

Revenue from mobile CBRS infrastructure will not be very significant compared with the giant RAN market. But this opportunity will grow from zero to about $250M, which is a significant leap for the small companies targeting the CBRS opportunity. There's no reason to believe that the cable MSOs, WISPs, and Private LTE deployments will be served by Ericsson and Nokia. A great deal of this revenue can be captured by Ruckus, Spidercloud/Corning, and other smaller suppliers.

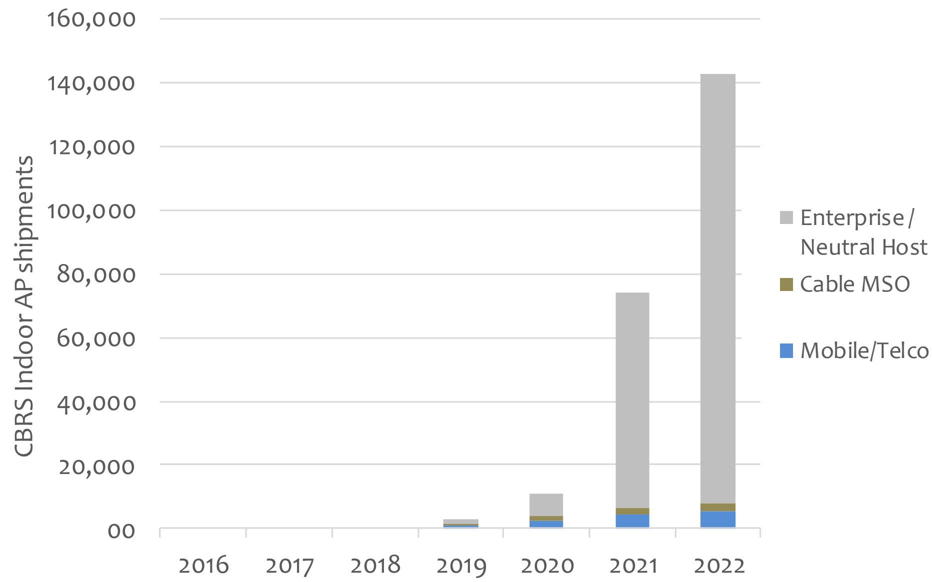


Source: Mobile Experts

Chart 20: CBRS Mobile AP revenue forecast, by operator type, 2016-2022

CBRS Indoor Access Forecast

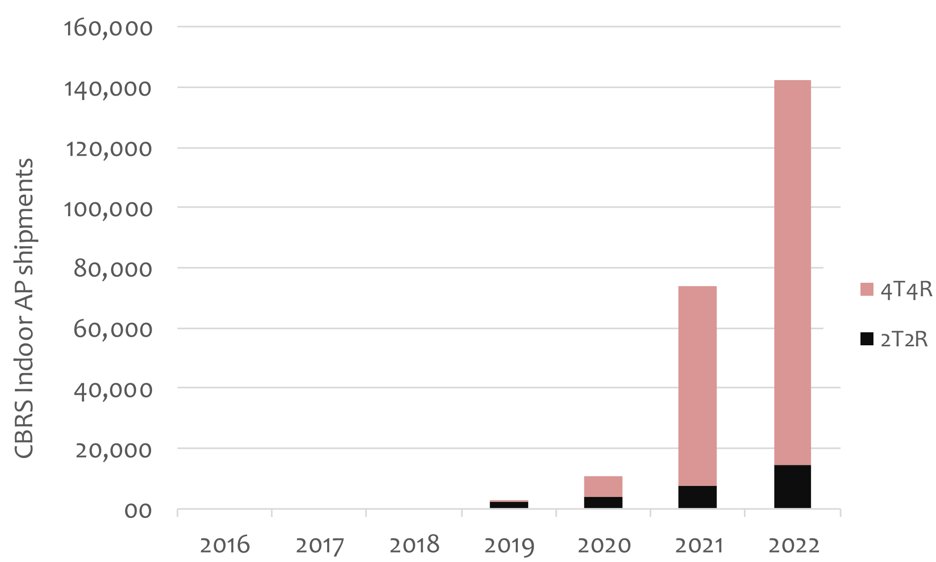
The indoor CBRS market will look somewhat different than fixed-wireless or outdoor markets. Indoor deployment will be fairly small from the mobile and cable operators, but we expect significant growth from venues that want public wireless services, as well as industrial companies.



Source: Mobile Experts

Chart 21: CBRS Indoor AP shipment forecast, by operator type, 2016-2022

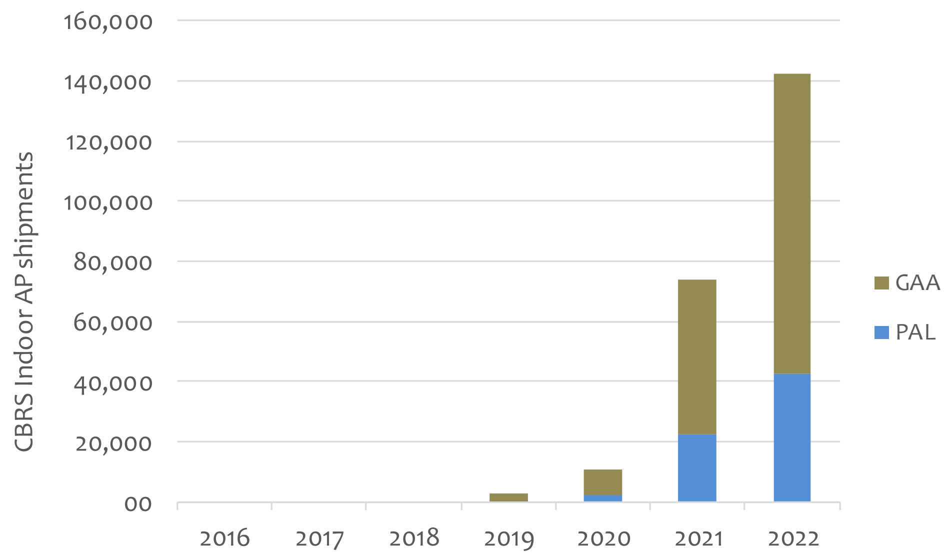
The indoor CBRS market will be closely tied to the availability of smartphones. A few early smartphones will use 2x2 MIMO technology but when the major smartphone platforms come out in the 2020 timeframe, we expect them to overwhelmingly support 4x4 because the same RF paths will also support 5G.



Source: Mobile Experts

Chart 22: CBRS Indoor AP shipment forecast, by MIMO order, 2016-2022

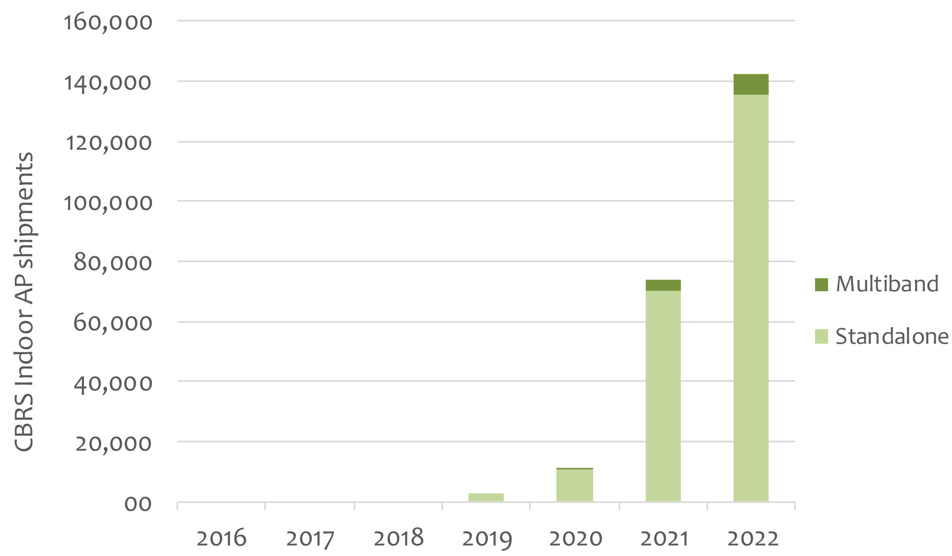
Most enterprises such as hotels or other large venues should be very comfortable with operating using a GAA license, as they have worked with Wi-Fi in the past and have no desire to get involved with PAL auctions. Large industrial Private LTE deployment could move toward PAL because these customers have a lot of money depending on the reliability of data. Deployment by operators is likely to be done under PAL licenses.



Source: Mobile Experts

Chart 23: CBRS Indoor AP shipment forecast, by GAA vs PAL, 2016-2022

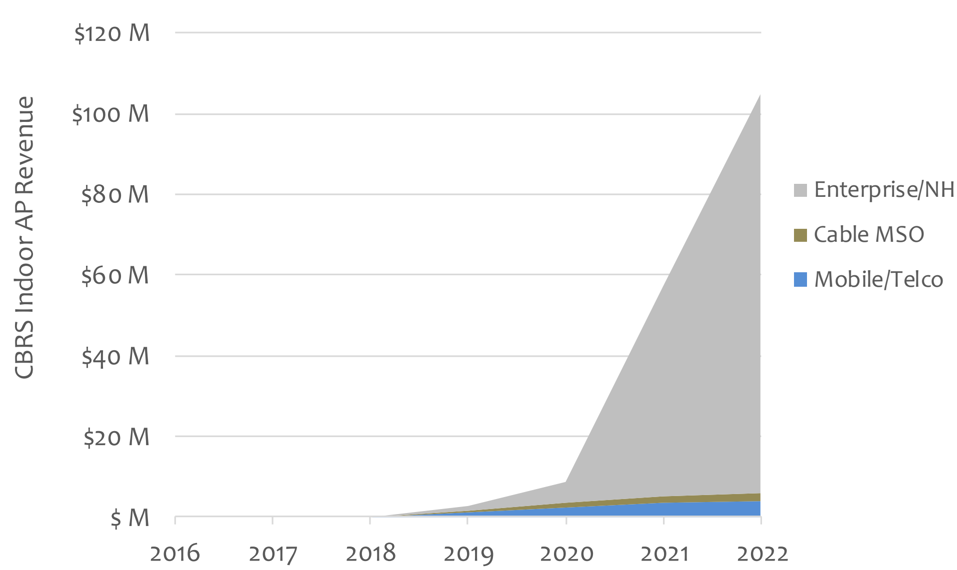
All Private LTE deployments should be single-band in nature, and even the deployments that are funded by operators are likely to use single-band CBRS in the indoor market. Cable operators certainly will use stand-alone CBRS small cells, and even mobile operators could use stand-alone CBRS in some cases.



Source: Mobile Experts

Chart 24: CBRS Indoor AP shipment forecast, multi-band vs standalone, 2016-2022

Revenue for indoor CBRS small cells will not be huge, because the small cells will be cheap devices with selling prices below $750 in the 2022 timeframe. Over time we anticipate that this segment could grow into the $80M range, mostly supporting Private LTE or Neutral Hosted networks.



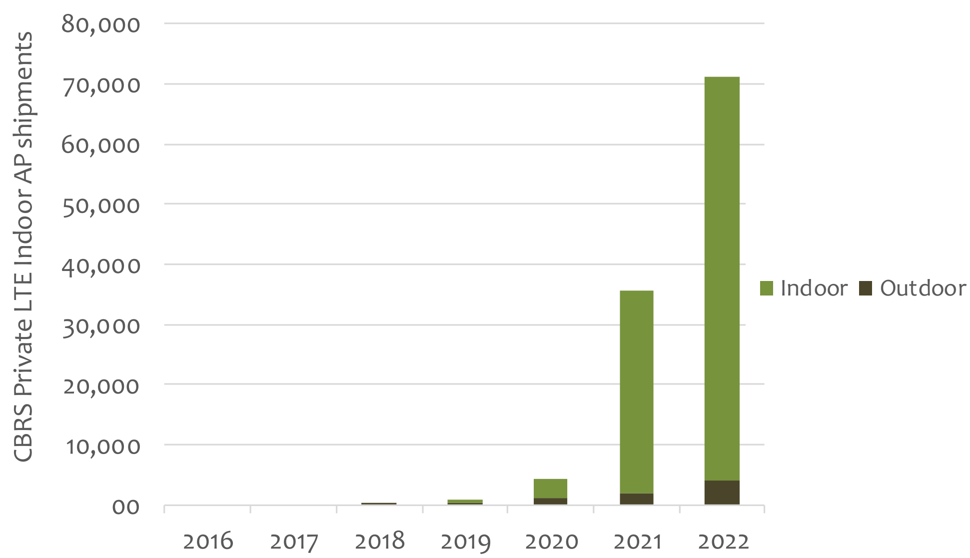
Source: Mobile Experts

Chart 25: CBRS Indoor AP revenue forecast, by operator type, 2016-2022

Private LTE Forecast

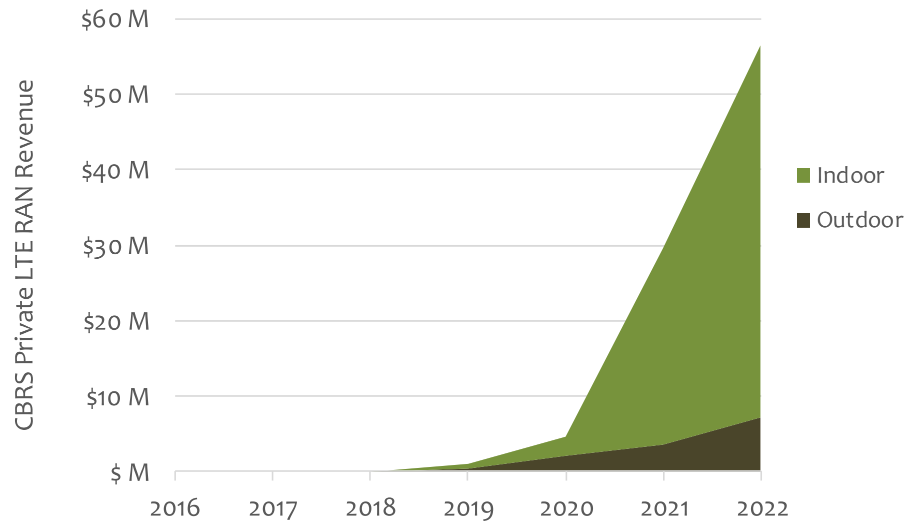
In the previous market segment (Indoor CBRS), we combined Enterprise deployment with Neutral Hosts, because many enterprises will use Neutral Hosts in order to deploy their Private LTE networks. In fact it may be difficult to distinguish between Private LTE and a Neutral Host CBRS network, as these systems could be set up for easy authentication and use by any smartphone that comes through.

To help in clarifying the market drivers behind deployment, we've isolated the deployments that are intended for truly private LTE use, for example in port operations, asset tracking, industrial IoT, or corporate smartphone access. The shipments and revenue shown in this segment should not be added to the Outdoor and Indoor CBRS market estimates, because Private LTE is already included in those numbers.



Source: Mobile Experts

Chart 26: CBRS Private LTE AP shipment forecast, indoor and outdoor, 2016-2022



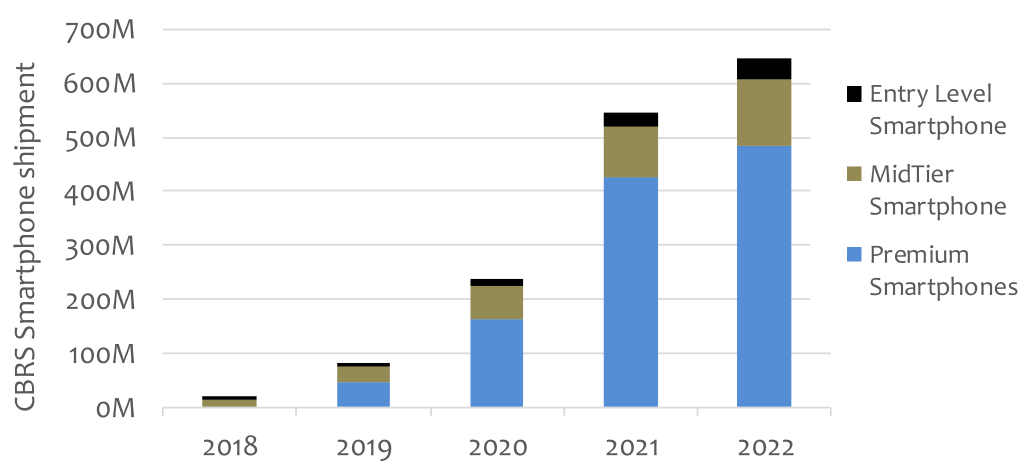
Source: Mobile Experts

Chart 27: CBRS Private LTE AP revenue forecast, indoor and outdoor, 2016-2022

CBRS Mobile Terminals Forecast

The smartphone market has not engaged in product development for CBRS like the infrastructure market has, so it's clear that the availability of smartphones and other CBRS terminals will lag behind the infrastructure. Major "flagship" smartphone platforms are not likely to include CBRS until 5G services in the 3.5 GHz band are also introduced in China, during late 2019 to 2020. Other smaller smartphone platforms will move more quickly.

For Private LTE networks, corporate employees are likely to get Dual SIM smartphones, so that they can enjoy access through the corporate LTE coverage indoors while using their normal LTE operator everywhere else. Apple doesn't support dual SIM yet, but they have recently filed some patents in this direction. Samsung supports dual SIM cards now.

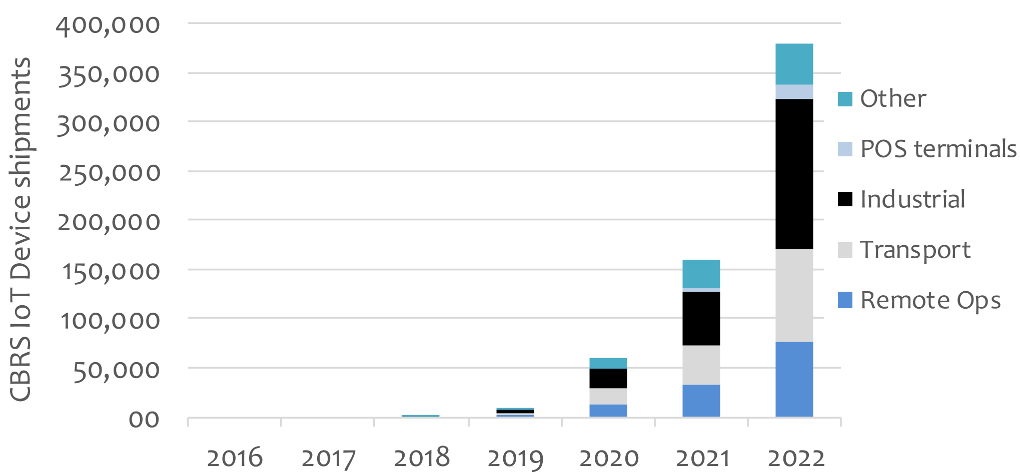


Source: Mobile Experts

Chart 28: CBRS-Enabled Smartphone forecast, by tier, 2016-2022

IoT devices are a bit more tricky, as multiple different market segments will drive the use of Private LTE. One of the biggest drivers today in industrial and transportation applications is the use of cameras to stream video. This can be for security purposes, or for safety in heavy industrial operations with cranes and robots moving around.

It's early days, so our initial forecast for Private LTE IoT splits the devices into mining, transportation, industrial, POS, and other applications fairly evenly. This tentative early forecast will be refined further as actual shipments prove the viability of each business application.



Source: Mobile Experts

Chart 29: CBRS Private LTE IoT Device forecast, by application, 2016-2022

6 ACRONYMS

2G: Second Generation Cellular

3G: Third Generation Cellular

3GPP: Third Generation Partnership Project

4G: Fourth Generation Cellular

802.1x: A security platform standard established by IEEE.

802.11: An umbrella standard which encompasses multiple unlicensed communications standards within the IEEE.

802.11a/b/g: Early generations of the 802.11 standard.

802.11n: The current generation of the 802.11 standard.

802.11ac: The generation of the 802.11 standard introduced in 2013.

802.11ad: An IEEE standard for 60 GHz short-range communications.

802.11ah: An IEEE standard for unlicensed communications below 1 GHz.

802.11ax: A future IEEE standard for very high throughput in Wi-Fi.

802.11i: An IEEE security specification for Wi-Fi networks.

802.11k: An IEEE standard for radio resource management to assist in limited mobility.

802.11r: An IEEE standard for rapid transition from one AP to another.

802.11u: The IEEE standard associated with Hotspot 2.0.

AAA: Authentication, Authorization, and Accounting (typically refers to the server which performs these functions).

AC: Alternating Current or Access Controller.

ACK: Acknowledgement.

AES: Advanced Encryption Standard.

ANDSF: Access Network Discovery and Selection Function.

Android: Google's mobile device operating system.

AP: Access Point (often referring to Wi-Fi access point)

APN: Access Point Name

ARPU: Average Revenue Per User

BSC: Base Station Controller

BTS: Base Transceiver Station

Bits/Hz/sec: Digital bits transmitted per Hertz of bandwidth per second

CA: Carrier Aggregation

CBRS: Citizens Broadband Radio Service, a shared wireless broadband use of the 3550-3700 MHz (3.5GHz) band in the US

CPE: Customer Premise Equipment (e.g., cable modem, broadband gateway)

dBm: Decibels of power relative to 1mW

DRS: Distributed Radio System

DSL: Digital Subscriber Line

EAP: Extensible Authentication Protocol.

EAP-AKA: EAP via Authentication and Key Agreement.

EAP-SIM: EAP via Subscriber ID Module.

EAP-TLS: EAP via Transport Layer Security.

EAP-TTLS: EAP via Tunneled Transport Layer Security.

EMEA: Europe, Middle East and Africa

eNB: eNodeB, or the radio access node for LTE

EPC: Evolved Packet Core.

ePDG: Evolved Packet Data Gateway.

GAA: General Authorized Access, applicable for the 3.5GHz shared spectrum, the lowest priority access, similar to unlicensed spectrum use

GB: Gigabyte

Gbps/km2: Gigabits per second per square kilometer

GHz: Gigahertz

GSM: Global System for Mobile communications, a 2G radio interface

GTP: GPRS Tunneling Protocol

GW: Gateway (normally referring to a femto gateway)

HARQ: Hybrid Automatic Repeat Request

HetNet: Heterogeneous Network

HEW: High Efficiency Wireless (now renamed 802.11ax)

HLR: Home Location Register.

HSPA: High Speed Packet Access

HSPA+: A subsequent evolution of HSPA with higher throughput

HSS: Home Subscriber Server

Hz: Hertz (cycles per second)

IEEE: Institute of Electrical and Electronics Engineers

IETF: Internet Engineering Task Force

IKEv2: Internet Key Exchange (version 2)

IP: Internet Protocol

IPSec: Internet Protocol Security

IPv4: Internet Protocol version 4

IPv6: Internet Protocol version 6

I-WLAN: Interworking for Wireless Local Area Networks.

LAN: Local Access Network

LTE-A: LTE Advanced, a higher bandwidth version of LTE

LAA: LTE-License Assisted Access, a 3GPP-compliant "official" LTE-U technology

LTE: Long Term Evolution, a "4G" radio interface based on orthogonal frequency division multiplexed data

LTE-U: LTE-Unlicensed, an "unofficial" technology to run LTE waveform on 5GHz unlicensed spectrum band

LWA: LTE/Wi-Fi Aggregation (use of LTE signals on both licensed control channels and licensed data channels, and Wi-Fi signals on unlicensed data channels).

MAC: Media Access Control layer

MHz: Megahertz

MIMO: Multiple Input, Multiple Output

MNO: Mobile Network Operator

MSO: Multi-Service (or System) Operator (reference to a cable operator)

MVNO: Mobile Virtual Network Operator

MulteFire: Standalone LTE-U technology whereby both control and data plane traffic flows in an unlicensed band

MU-MIMO: Multi-User MIMO.

NGH: Next Generation Hotspot (Hotspot 2.0)

OEM: Original Equipment Manufacturer

OFDM: Orthogonal Frequency Division Multiplexed

PAL: Priority Access License, applicable for the 3.5GHz band, second highest priority in use of the 3.5GHz shared spectrum

Passpoint: A certification stamp for Hotspot 2.0 equipment, administered by Wi-Fi Alliance

PC: Personal Computer

QoS: Quality of Service

RAN: Radio Access Network

RF: Radio Frequency

SAS: Spectrum Access System, a software system to coordinate spectrum sharing (although it can be applied across all shared spectrum, its use is primarily focused on 3.5GHz CBRS)

SIP: Session Initiation Protocol

SNR: Signal-to-Noise Ratio

SSID: Service Set Identification

TD-LTE: Time Domain based Long Term Evolution

UE: User Equipment

VAR: Value Added Reseller

W: Watts

WCDMA: Wideband Code Domain Multiple Access, a 3G radio interface

Wi-Fi: Wireless Fidelity (802.11 data communications)

WISP: Wireless Internet Service Provider

WLAN: Wireless Local Area Network

7 METHODOLOGY

To create estimates and forecasts for the CBRS market, Mobile Experts relied on direct input from more than 30 industry sources, with many different mobile, cable, and ISP operators contributing to the overall analysis to give a detailed global view of the market. Mobile Experts has also spoken with more than 40 other companies in related business areas for Carrier Wi-Fi, LTE-U, and LTE business areas—providing some valuable cost estimates and background data for potential CBRS growth.

Mobile Experts built a "top down" forecast based on direct input from mobile operators, cable operators, neutral host companies, and wireless Internet service providers (WISPs). . Then, Mobile Experts built a "bottom up" forecast through discussions with OEMs, software developers, and semiconductor suppliers in the supply chain. For this early market, financial disclosures were not useful, so we relied on our cost analysis to make predictions about the likely course of technology choices for each business model.

Private LTE deployment was considered as a part of the overall CBRS market. Some Private LTE systems will be deployed by Neutral Host companies, then owned by the Enterprise. We consider these to be Private LTE networks. Other systems (in public buildings such as hotels or stadiums) will be owned by the Neutral Host, with coordination with Verizon/AT&T/T-Mobile to support multi-operator access. These are not included in the Private LTE totals.

For handset and IoT device forecasts, Mobile Experts interviewed multiple suppliers in the handset market to determine the maturity of RF filter technology and the software to support the unique restrictions of CBRS operation. Our direct interviews resulted in the delayed timing of the forecast reflected throughout this report.